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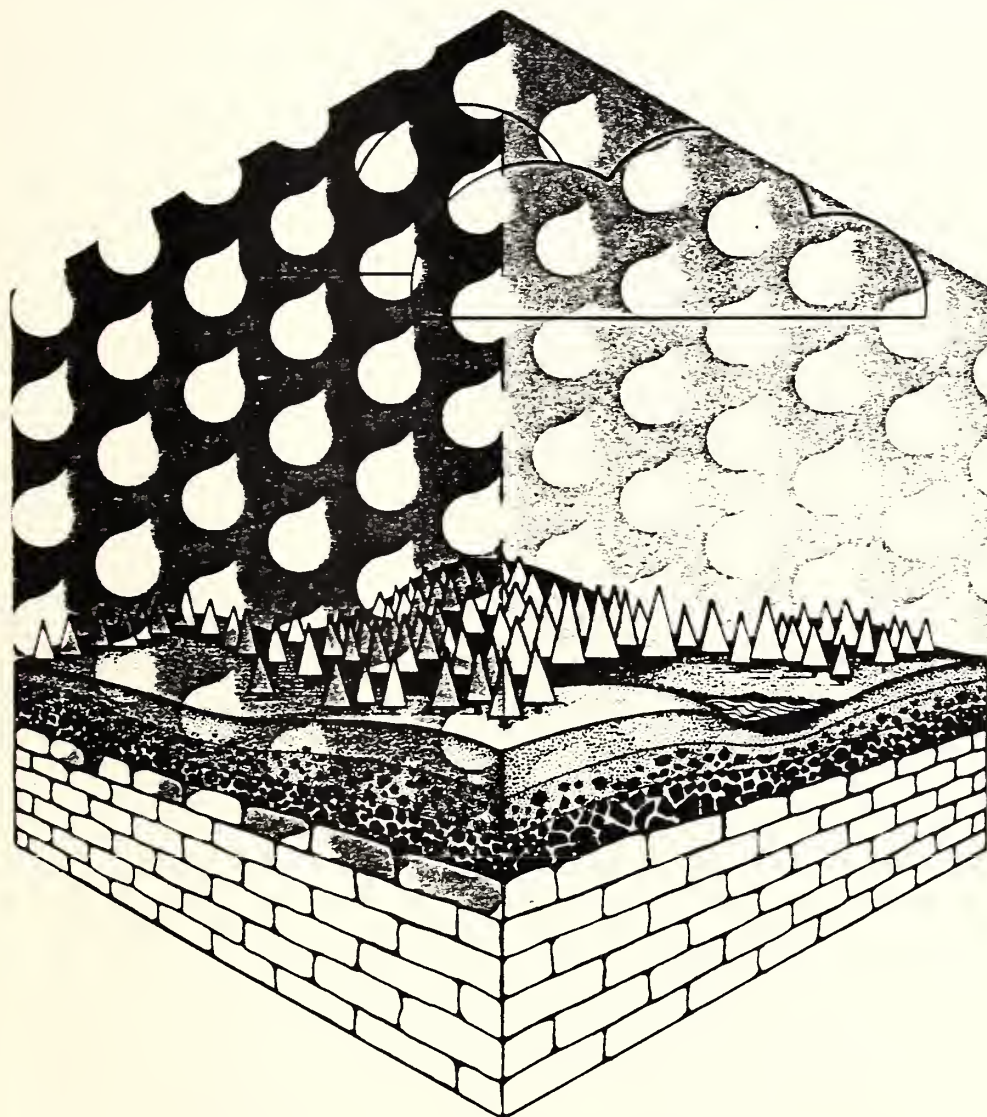
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THE STRAWBERRY CREEK AND PYRAMID GUARD STATION LANDSLIDES

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Geology

By


Steven Francis Connelly

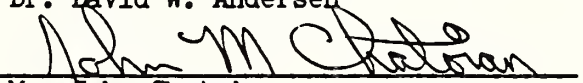
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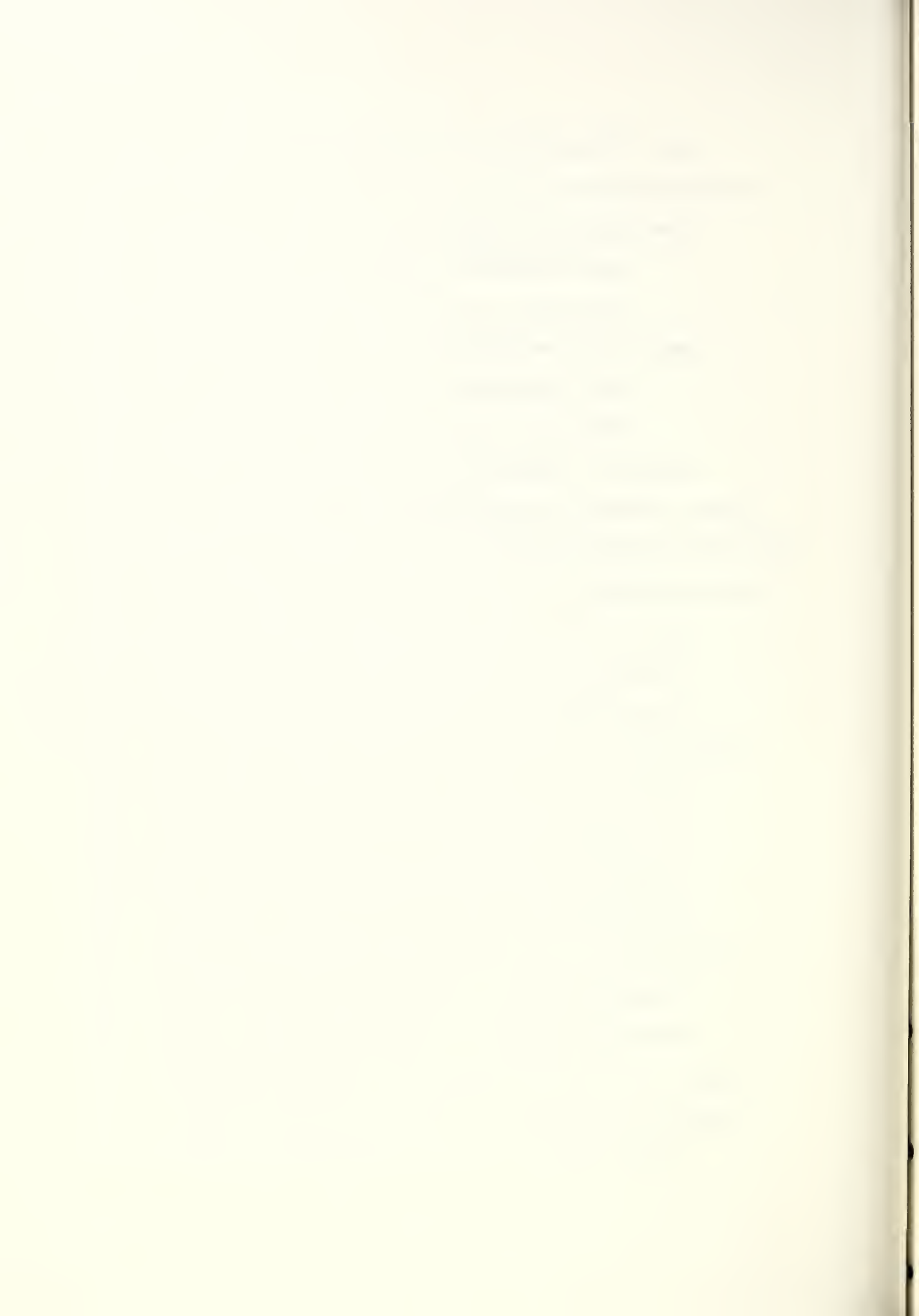


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## ABSTRACT

The Strawberry Creek landslide and the Pyramid Guard Station landslide are large catastrophic debris flows that occurred in the Eldorado National Forest during the spring of 1983. The landslides are located within 3.5 miles of one another near the community of Strawberry, California.

The debris flows occurred within a 5 day time period during the spring of 1983 following a record snowfall season in the Sierra Nevada. The debris flows were triggered by a record snowmelt during a two-week-long heatwave in the end of May, 1983.

The debris flows mobilized from shallow soil slips that occurred within topsoil and colluvial materials containing less than 1 percent clay-sized material. Secondary debris flows involving weathered granodioritic bedrock material were associated with each landslide.

The landslides exhibit contrasting characteristics such as vegetation, source area slope, fire history, and landslide history. The Strawberry Creek landslide occurred in heavily forested terrain with a source area slope of approximately 31 degrees. No evidence of other recent debris-flow activity was observed in the vicinity of the landslide. The Pyramid Guard Station landslide, in contrast, occurred in sparsely vegetated and recently burned terrain with a source area slope of approximately 26 degrees. Evidence of recurrent debris-flow activity was observed in the vicinity of the landslide.



Carbon-14 dates of charcoal fragments sampled from layered debris-flow deposits at the toe of the Pyramid Guard Station landslide indicate that five debris-flow events have occurred in the Pyramid Guard Station drainage in the last 325 y.b.p. In addition, two older debris-flow deposits have been dated at 1770 and 2086 y.b.p.

The landslides share common characteristics such as granodiorite parent material, southwest aspect, and headscarp elevation. The headscarps of both debris flows occur at about the same elevation, and both are located on slopes with similar southwest aspects. These characteristics indicate that similar snowpack and snowmelt conditions existed, and these probably were dominant factors in controlling both landslides.

A mechanical analysis indicates that groundwater levels of 1.6 feet and 2.3 feet above potential slip surfaces would have been required to initiate the failures of the Strawberry Creek and Pyramid Guard Station landslides, respectively. A higher groundwater level was required for the Pyramid Guard Station landslide because of the more gentle slope within its source area.

Significant findings include: 1) snowmelt generates debris-flow landslides in the Sierra Nevada, 2) debris flows may occur in weathered granitic materials containing less than 1% clay-sized material, and 3) debris-flow landsliding has been a recurrent phenomena in the Sierra Nevada.



## INTRODUCTION

Two large catastrophic debris flows, the Strawberry Creek landslide and the Pyramid Guard Station landslide, were triggered within a five day time period during the spring of 1983, near the small mountain community of Strawberry, California. The Strawberry Creek landslide occurred on May 31, 1983, and the Pyramid Guard Station landslide occurred on June 4, 1983. The landslides are within 3.5 miles of one another on similar southwest-facing mountain slopes. The source areas of the landslides are at almost identical elevations of approximately 7,500 feet, and the landslides involved materials derived from similar granodiorite bedrock.

The landslides share similar characteristics, which include their location, date of failure, aspect, parent material, source area elevation, and debris-flow mode of failure. The similarities suggest that the landslides may have been initiated and or controlled by similar conditions.

The purpose of this study was to map and document the physical characteristics of the Strawberry Creek and Pyramid Guard Station landslides, to investigate the climatic conditions leading to the failures, to compare and contrast the characteristics of the two landslides, and to identify conditions controlling the landslide failures.



### Location

The Strawberry Creek and Pyramid Guard Station landslides are in the Eldorado National Forest, southwest of Lake Tahoe, California (Fig. 1). U.S. Highway 50 transects the Eldorado National Forest in a northwest direction. The crest of the Sierra Nevada mountain range



Figure 1. Regional location map.

Location

The Strawberry Creek and Potomac Grant located in the  
the Kibbick National Forest, southeast of Lake Tahoe, within  
1) U.S. Highway 50 traverses the Kibbick National Forest  
northwest direction. The crest of the Sierra Nevada range is



parallels the eastern boundary of the forest and reaches elevations close to 10,000 feet above sea-level within the forest.

The Strawberry Creek and Pyramid Guard Station landslides are near the mountain resort community of Strawberry, California (Fig. 2).

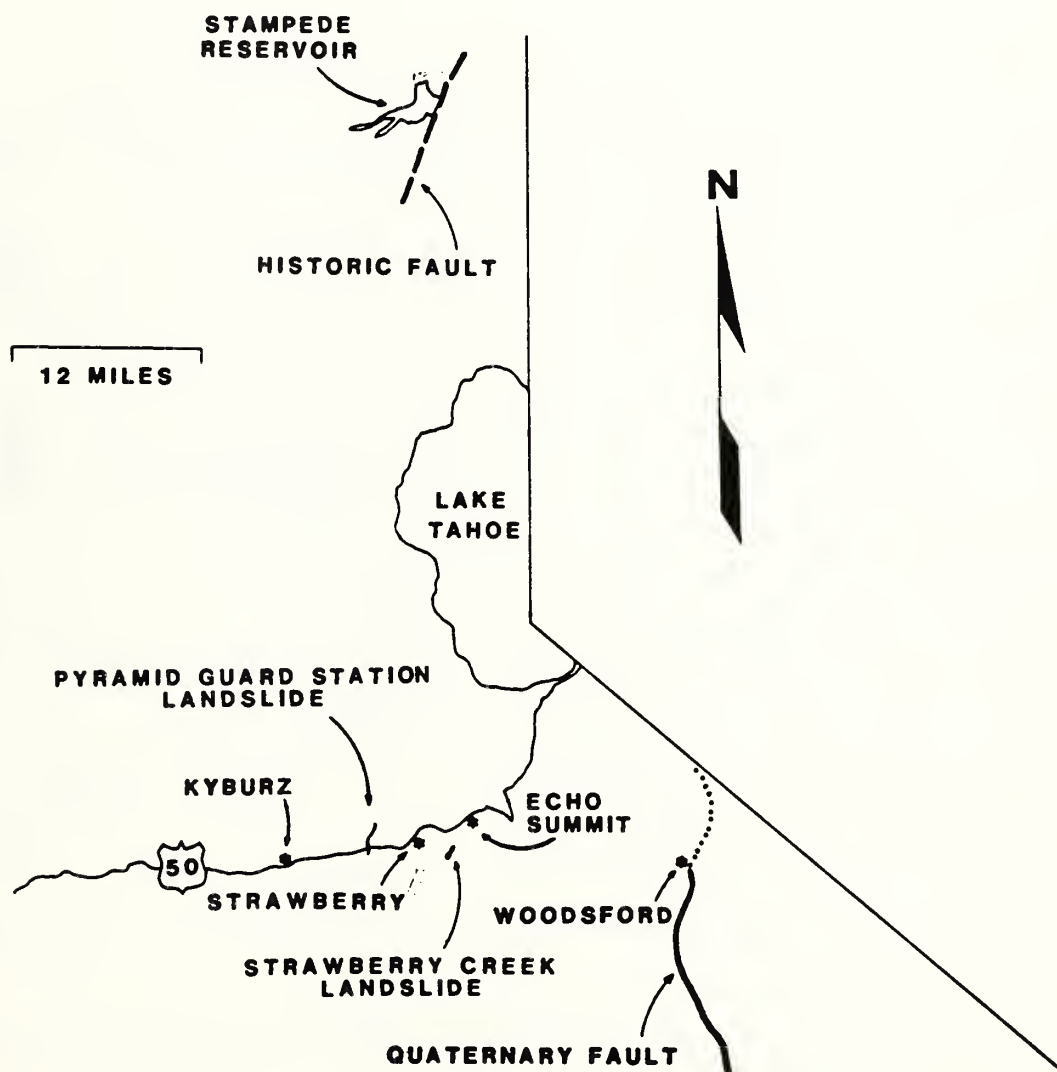


Figure 2. Vicinity map showing potentially active faults (after Jennings, 1975).



Strawberry is situated along U.S. Highway 50 about 11 miles southwest of Lake Tahoe at an elevation of approximately 5,760 feet.

The Strawberry Creek landslide is located approximately 2 miles southeast of Strawberry (Fig. 3) on a mountain slope on the north side of Strawberry Creek Canyon. Strawberry Creek is a tributary of the

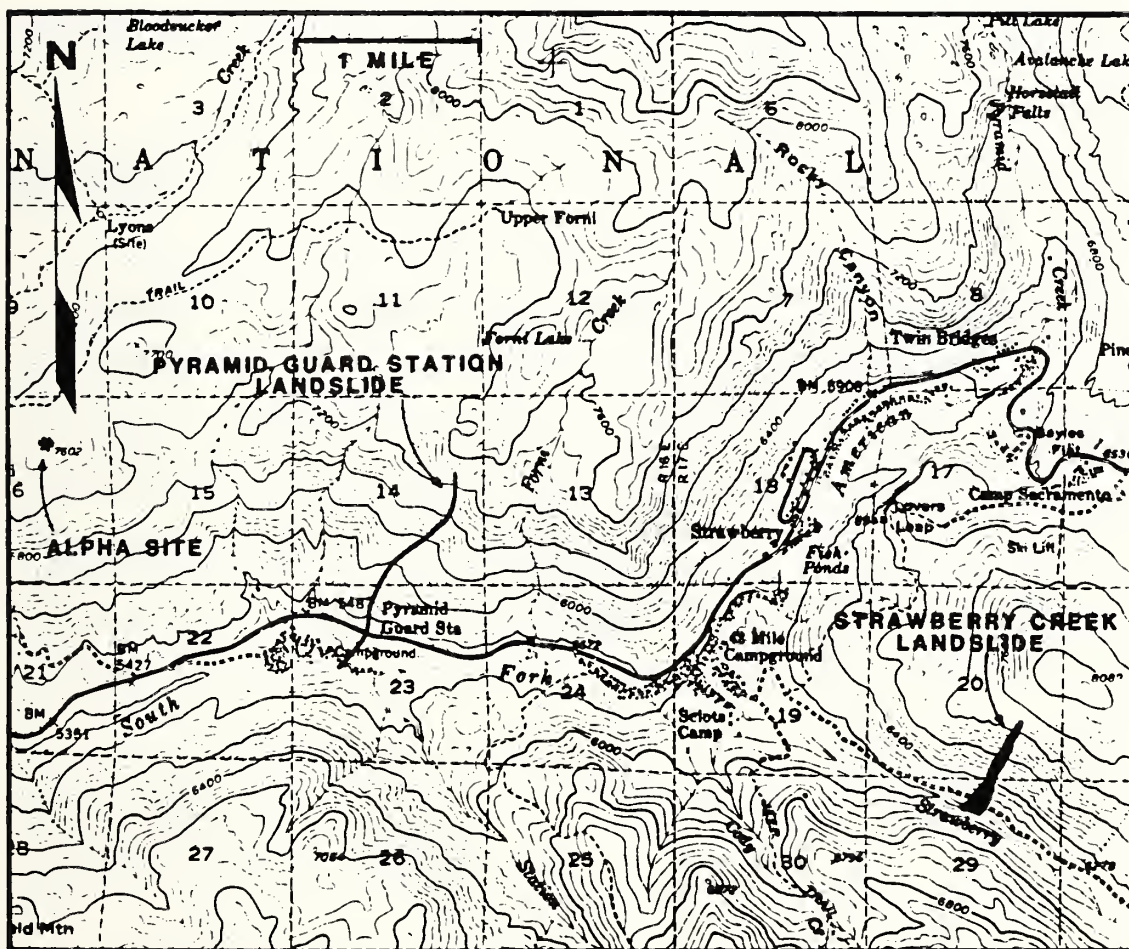


Figure 3. Site location map, USGS 15 Minute, Fallen Leaf Lake quadrangle, 80 foot contour interval.



South Fork of the American River. The Strawberry Creek landslide damaged a logging and recreational road near the base of the slope.

The Pyramid Guard Station landslide is located approximately 3.5 miles northwest of the Strawberry Creek landslide (Fig. 3). The Pyramid Guard Station landslide occurred on a mountain slope on the north side of the American River canyon. The landslide temporarily closed U.S. Highway 50 after it deposited debris on the road approximately 300 feet west of Pyramid Guard Station.

### Map Scales

Topographic base maps for this study were photogrammetrically produced by the U.S. Forest Service Geomtronics at a compilation scale of 1:3,000 from color aerial photograph stereo pairs taken on September 4, 1983 at a scale of 1:12,000. Field data were recorded on base maps at an enlarged scale of approximately 1:1,500. Data from the field maps were later reduced and transferred to maps at the 1:2,400 scale of Plates 1 and 2.

### Aerial Photographic Mapping

Surficial geologic units delineated as granodiorite bedrock, soil and colluvium, or alluvium were mapped on the 1983 aerial photographs (App. A) and photogrammetrically enlarged to the 1:2,400 final map scale (Plates 1 and 2). Units of soil and colluvium, or bedrock were



mapped based upon the relative density of bedrock outcrops distinguishable in the photographs. Areas where tree cover obscured the ground surface were mapped as units of soil and colluvium. Alluvium was mapped only in active streams where significant deposits have accumulated. Map contacts of surficial geologic units shown on Plates 1 and 2 are approximate, and are considered accurate within 25 feet.

### Field Techniques

Field mapping and sampling were primarily performed between April and November of 1985. Additional field visits were made during the summers of 1986 and 1987. A Brunton compass and a Thommen altimeter, accurate to approximately plus or minus 10 feet in elevation, were utilized. Due to the superior quality and detail of the topographic base maps, mapped features such as landslide scarps, depositional contacts, and sample locations are considered accurate to within plus or minus 10 feet.

Field descriptions of landslide deposits were performed in general conformance with the Unified Soil Classification System (Wagner, 1957). Descriptions of color were made according to the Munsell Soil Color Chart (1975). Field descriptions include estimates of the percentages of organic material and of the very coarse-grained materials such as cobbles and boulders.



### Laboratory Methodology

Grain size analyses were performed on samples of landslide deposits for classification and correlation purposes. Grain size distribution curves, presented in Appendix B, were determined by sieve and hydrometer analyses using the ASTM Standard Test Designation: D 422-63 (1984). Approximately 400 g of material were collected for each analysis. Cobble-sized and larger material was excluded in the field sampling procedure. Estimates of the larger size fraction of the deposits are provided in the field descriptions. Nested sieves were used with opening sizes of 2 mm, 0.991 mm, 0.5 mm, 0.25 mm, 0.124 mm, and 0.063 mm. Hydrometer analyses were performed on silt- and clay-sized material finer than 0.063 mm for selected samples of landslide deposits.



## REGIONAL GEOLOGY

The Pyramid Guard Station and Strawberry Creek study areas are on the western flank of the northwest-trending Sierra Nevada mountain range and are in the Fallen Leaf Lake 15-minute quadrangle. The geology within the quadrangle was mapped and described by Loomis (1981). A regional geologic map after Loomis is presented as Figure 4.

Basement rocks in the area predominantly consist of Cretaceous granitic and dioritic rocks that underlie and intrude isolated roof pendants of Jurassic metasedimentary and metavolcanic rocks. Miocene volcanic rocks occur near the southern edge of the quadrangle and Quaternary glacial deposits mantle the South Lake Tahoe Valley and isolated regions to the north of the subject landslides.

According to Loomis (1981), the present geomorphic landscape within the region is primarily a result of alpine glaciation that has shaped uplifted bedrock surfaces. Evidence of previous erosional episodes, superimposed on the bedrock surfaces, indicates that successive stages of uplift have occurred (Loomis, 1981). More recent stream action and mass wasting processes have shaped the mountain slopes upon which the subject landslides are located.



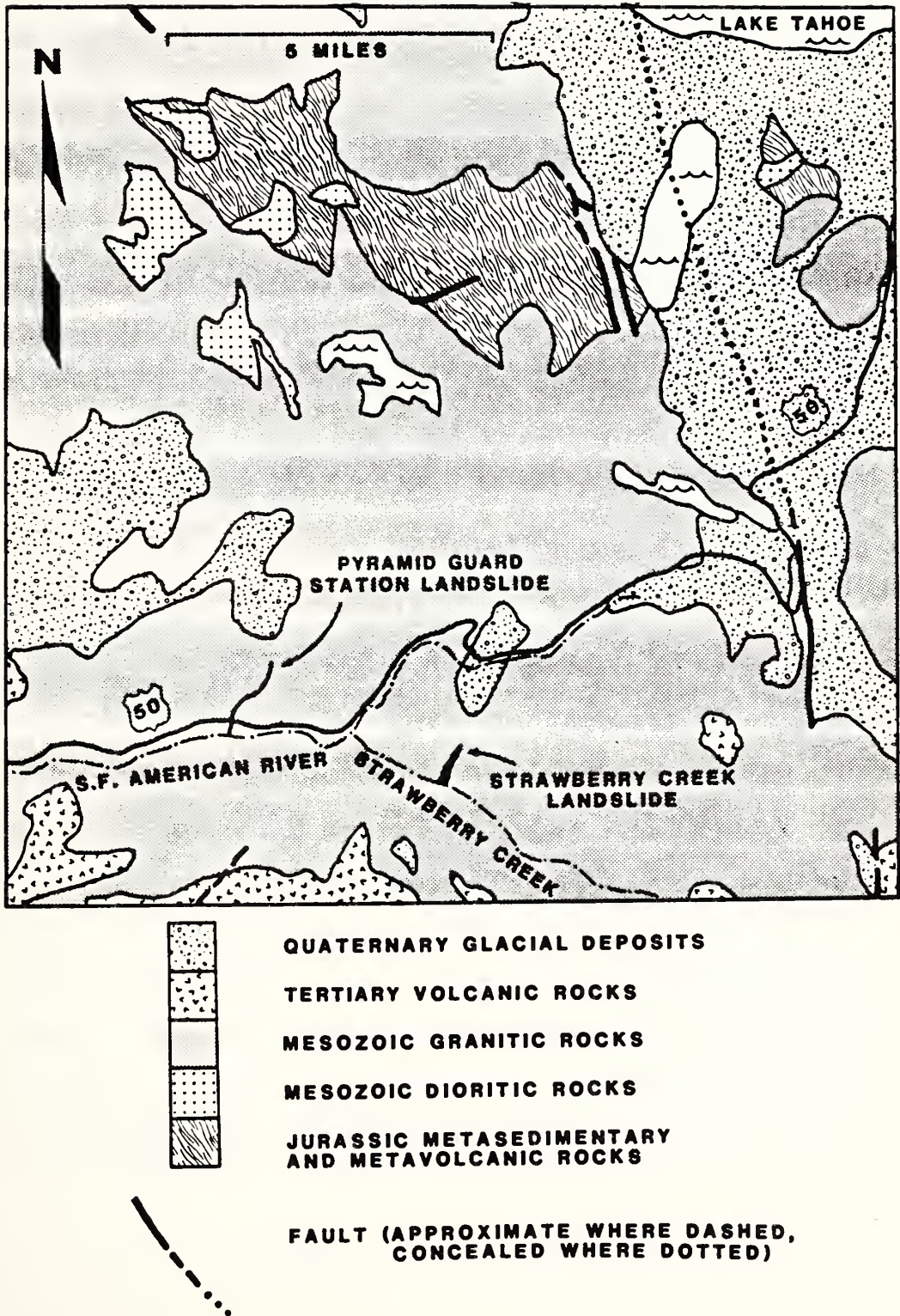


Figure 4. Regional geologic map (simplified after Loomis, 1981).



## SEISMICITY

Two potentially active faults are in the vicinity of the study area (Jennings, 1975). An unnamed, historically active fault that trends north-south is located approximately 42 miles to the north of the study area near Stampede Reservoir (Fig. 2). An unnamed Quaternary fault that has not been historically active and also trends north-south is located approximately 18 miles to the east of the study area near the community of Woodsford (Fig. 2).

Seismic records of the National Earthquake Information Service (1983) indicate that there were no significant earthquakes in the Sierra Nevada or in the Western United States on the dates of the subject landslide failures, or during that general time period during late May and early June of 1983. The closest significant seismic event that could have potentially been felt in the study area was the devastating 6.2 magnitude earthquake that occurred on May 2, 1983, near Coalinga, California, approximately 180 miles to the south (Fig. 1). Aftershocks associated with this event continued throughout May and early June of 1983. Minor aftershocks centered in the Coalinga area coincidentally occurred on the dates of both of the subject landslides, but these earthquakes probably did not trigger the landslide events.



## CLIMATIC CONDITIONS

Temperatures in the areas of the Strawberry Creek and Pyramid Guard Station landslides vary, in degrees Fahrenheit, from the low teens during mid-winter to the low 80's during mid-summer. The study areas are typically covered with snow during the months of November through May.

Precipitation and temperature data have been collected by the Pacific Gas & Electric Company (1985) at a power intake along the South Fork of the American River near Kyburz, California. Kyburz is located about 8 miles west of Strawberry at an elevation of approximately 4,000 feet. A graph of cumulative yearly precipitation (rainfall and equivalent snowfall) recorded at Kyburz is presented in Figure 5 for

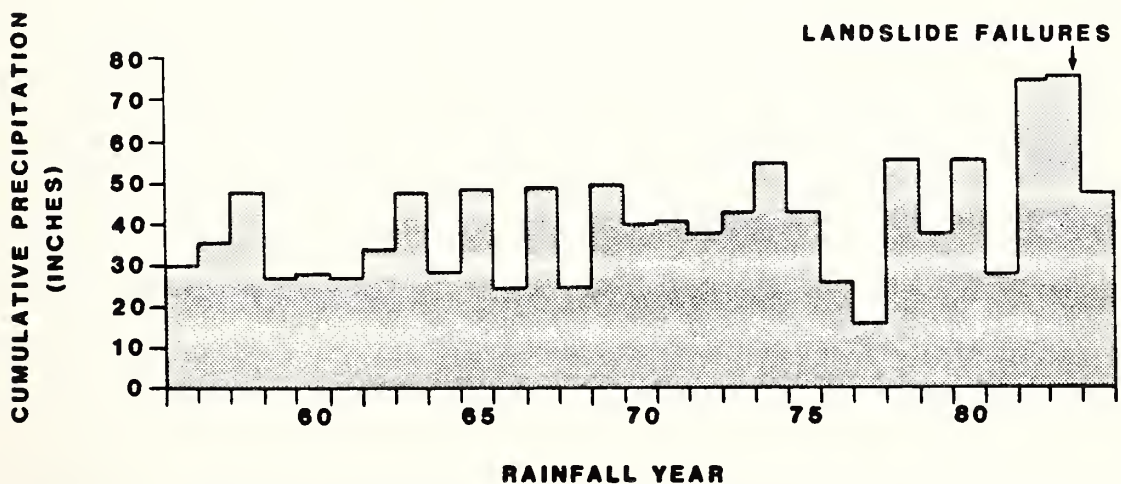


Figure 5. Cumulative yearly precipitation measured at Kyburz, California (Pacific Gas & Electric Company, 1985).



the 1956 to 1984 rainfall years. A rainfall year begins in October of the previous year and ends in September of the rainfall year. During that 29 year time period, Kyburz received an average of approximately 41 inches of precipitation per rainfall year.

A record amount of precipitation of 75 inches was measured at Kyburz during the 1982 rainfall year. A severe thunderstorm occurred in June of 1982, during which the most intense rainfall ever recorded in the Sierra Nevada was measured near Pyramid Guard Station (Goodridge, 1982).

The 1983 rainfall year, during which the Strawberry Creek and Pyramid Guard Station landslides occurred, was also a record year. The recording station at Kyburz measured 76 inches (the largest amount of precipitation measured over the 29 year time period) during the 1983 season. The 1982 and 1983 rainfall year combination was the wettest period ever recorded in the Sierra Nevada (Kuehn, 1984).

Snowfall and snowpack measurements have been collected by the California Department of Transportation (1985) at Echo Summit, California. Echo Summit is located approximately 7 miles east of the study area (Fig. 2) at an elevation of approximately 7,400 feet (similar to the elevations of the source areas of the subject landslides). A graph showing the cumulative seasonal snowfall and maximum seasonal snowpack recorded at Echo Summit between 1963 and 1985 is presented in Figure 6. During the 1983 season, Echo Summit received 132 percent of the average total seasonal snowfall and 127 percent of the average maximum seasonal snowpack for the 23 year time period.



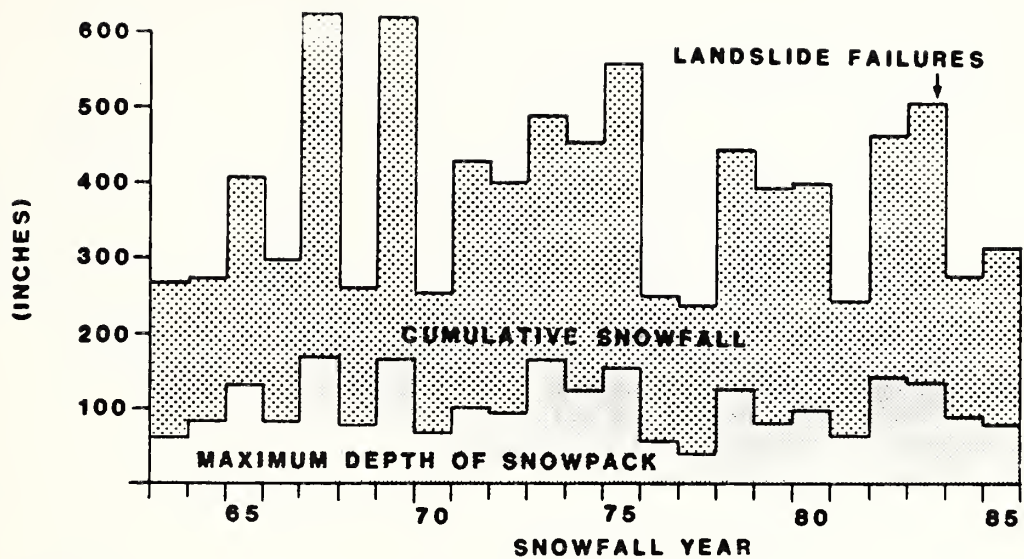


Figure 6. Cumulative seasonal snowfall and maximum seasonal snowpack measured at Echo Summit, California (California Department of Transportation, 1985).

A graph of cumulative monthly precipitation recorded at Kyburz from 1980 through 1984 is presented in Figure 7 (Pacific Gas & Electric Company, 1985). These data indicate that precipitation in the area is concentrated during the months of October through May, with only slight amounts of precipitation during the months of June through September.

Temperature data have been collected by the Sacramento Municipal Utility District (1983) at Alpha site. Alpha site is a snow survey station located on a ridge approximately 2 miles northwest of Pyramid Guard Station (Fig. 3). Alpha site is at an elevation of 7,600 feet (similar to the elevations of the source areas of the subject landslides). Daily temperature data recorded at Alpha site for April 1 through June 5, 1983 are presented in Figure 8.



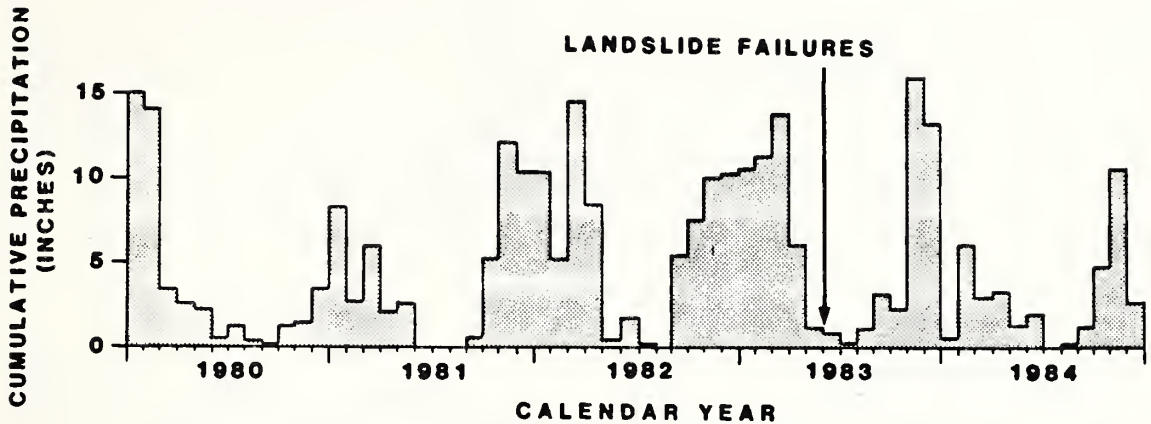


Figure 7. Cumulative monthly precipitation measured at Kyburz, California (Pacific Gas & Electric Company, 1985).

Daily precipitation and stream discharge level data collected by the Pacific Gas & Electric Company at Kyburz are presented in Figure 8 for the same time period. Stream level data were measured from a water stage recorder on the South Fork of the American River.

A two-week-long heatwave, starting on May 17 and ending on about May 31, immediately preceded the failures of the subject landslides. An average daily maximum temperature of 58 degrees Fahrenheit and an average daily minimum temperature of 42 degrees Fahrenheit were measured at Alpha site during the heatwave. A peak temperature recorded during the heatwave of 67 degrees Fahrenheit occurred on May 26. Approximately 1 inch of rainfall was recorded at Kyburz during the first two weeks of May and no precipitation was recorded during the heatwave. About 1/2 inch of rainfall was measured at Kyburz on June 2.



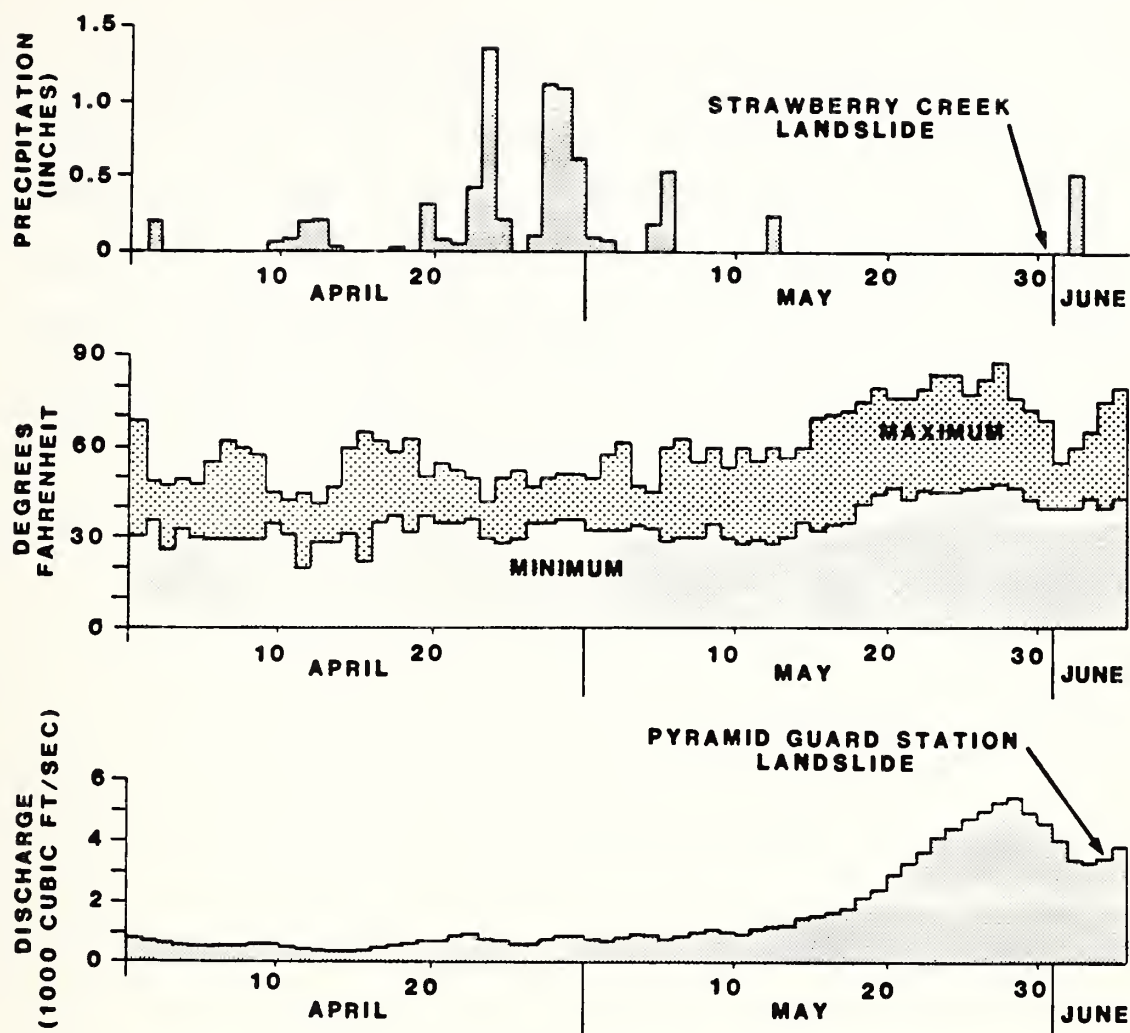


Figure 8. Daily precipitation (Pacific Gas & Electric Company, 1985), maximum and minimum temperatures (Sacramento Municipal Utilities District, 1983), and stream discharge levels (P. G. & E., 1985) for April through early June, 1983 (precipitation and stream discharge data collected at Kyburz, temperature data collected at Alpha site).

The heatwave produced record amounts of snowmelt and runoff. Unusually high stream discharge levels on the South Fork of the American River were measured at Kyburz during late May. The peak discharge level for the 1983 rainfall year was recorded on May 29.



In summary, the Sierra Nevada received record amounts of precipitation for the 1983 rainfall year during which a deep snowpack developed in the study area. A two-week-long heatwave preceded the failures of the subject landslides. The heatwave produced record snowmelt conditions, and record stream levels were measured on the South Fork of the American River. No significant precipitation was measured during the month preceding the landslide failures.



## STRAWBERRY CREEK LANDSLIDE

On May 31, 1983, Pacific Gas & Electric Company employees working on a canal intake located along the South Fork of the American River near Kyburz, California, noticed an unusual amount of silt in the river. The employees followed the silt upstream to Strawberry Creek, which joins the South Fork of the American River about 7 miles east of Kyburz. The P.G. & E. workers discovered the source of the silt about 2 miles up Strawberry Creek. Silt and debris were washing downstream from a massive landslide that had dammed the creek.

The Strawberry Creek landslide, shown on Figure 9 and on Plate 1, initiated as a shallow soil slip on the upper portion of the mountain slope forming the the north side of the Strawberry Creek canyon. The crown of the landslide is located at an elevation of 7,490 feet. The soil slip developed into a rapid debris flow or debris avalanche as it progressed downslope, uprooting trees and scouring away soil and colluvium. The body of the landslide split into three separate flows halfway down the slope. Further downslope, the three landslide flows scoured away a logging road that parallels Strawberry Creek. Debris composed of soil, rock, trees, ice, and snow was deposited into Strawberry Creek creating a temporary dam. The temporary dam was breached and much of the granular landslide debris had washed downstream the day after the failure when Forest Service personnel arrived on the scene (Kuehn, personal communication 1985).





Figure 9. Aerial photograph of the Strawberry Creek landslide looking towards the northeast. Strawberry Creek drains from right to left at the base of the landslide. The Lake Tahoe basin and the Sierra Nevada crest are located in the far background.



## Physical Setting

### Slope

The Strawberry Creek landslide is on a southwest-facing mountain slope with an average gradient of approximately 25 degrees from the ridgetop above to the creek at its base. The northwest-trending ridgetop above the landslide is at an elevation of approximately 8,060 feet, 560 feet above the landslide crown. Strawberry Creek is located at the base of the slope at an elevation of approximately 6,060 feet.

Slope Profile A-A', shown on Plate 3, depicts the slope from the ridgetop, through the landslide, and to the creek bottom below. The lower third of the profile above Strawberry Creek has an average gradient of approximately 24 degrees. A minor bench marked by natural bedrock outcrops is located at an elevation of about 6,800 feet. The slope above the bench increases to a gradient of approximately 30 degrees. A break-in-slope occurs within the source area of the landslide at an elevation of about 7,400 feet. The gradient steepens above 7,400 feet to approximately 38 degrees. The slope gradually decreases, above an elevation of about 7,800 feet, to the relatively flat ridgetop.



## Vegetation

The majority of the mountain slope in the vicinity of the landslide is densely forested with mature red fir and white fir. Several clearings vegetated with grasses and brush are located within the forest along the slope. The forest gives way to dense manzanita and brush approximately above the 7,400 foot contour level.

## Surface Water

Several springs, shown on Plate 1, are located along the western margin of the landslide at an elevation of approximately 6,810 feet. A number of springs occur within and at the margins of the landslide near the 7,280 foot contour level. Water was actively seeping from the springs within the landslide at that elevation during field investigations of the summer of 1985. There are no major drainages on the slope near the landslide. However, a minor ephemeral creek located near the northwest margin of the landslide is evident in aerial photographs taken prior to the landslide failure.

## Site History

No evidence of previous landslide activity in the immediate vicinity of the Strawberry Creek landslide was detected in a review of aerial photograph stereo pairs dating from 1966, 1973, and 1980. A list of the aerial photographs reviewed is presented in Appendix A. It is



apparent from the aerial photographs that the logging road located above Strawberry Creek had been constructed prior to 1957. Kuehn and Bedrossian (1987) indicated that the mountain slope in the vicinity of the landslide has never been logged.

### Site Geology

#### Bedrock Geology

The Strawberry Creek landslide is underlain by bedrock described by Loomis (1981) as the Lovers Leap granodiorite, an intrusive igneous body covering a 15-square-mile area (Fig. 4). Loomis has mapped vertical to steeply dipping foliations within the granodiorite along the ridgetop above the landslide. The foliations strike northwest, parallel to the trend of the ridge. Everden and Kistler (1970) have measured a Cretaceous radiometric age of 94 m.y. for the Lovers Leap granodiorite.

#### Surficial Geology

Generalized units of surficial geology in the vicinity of the Strawberry Creek landslide are delineated on Plate 1. Recent alluvium, composed predominantly of coarse-grained stream sediments, are exposed within the Strawberry Creek drainage. Soil and colluvium, composed of fine- to coarse-grained residual soils and slope wash material are exposed predominantly between the creek and the 7,400 foot contour level. Several irregularly-shaped bedrock units composed of rock



outcrops with thin to very thin soil cover, also occur on the lower slope. Bedrock outcrops predominantly occur above 7,400 feet.

### Soils

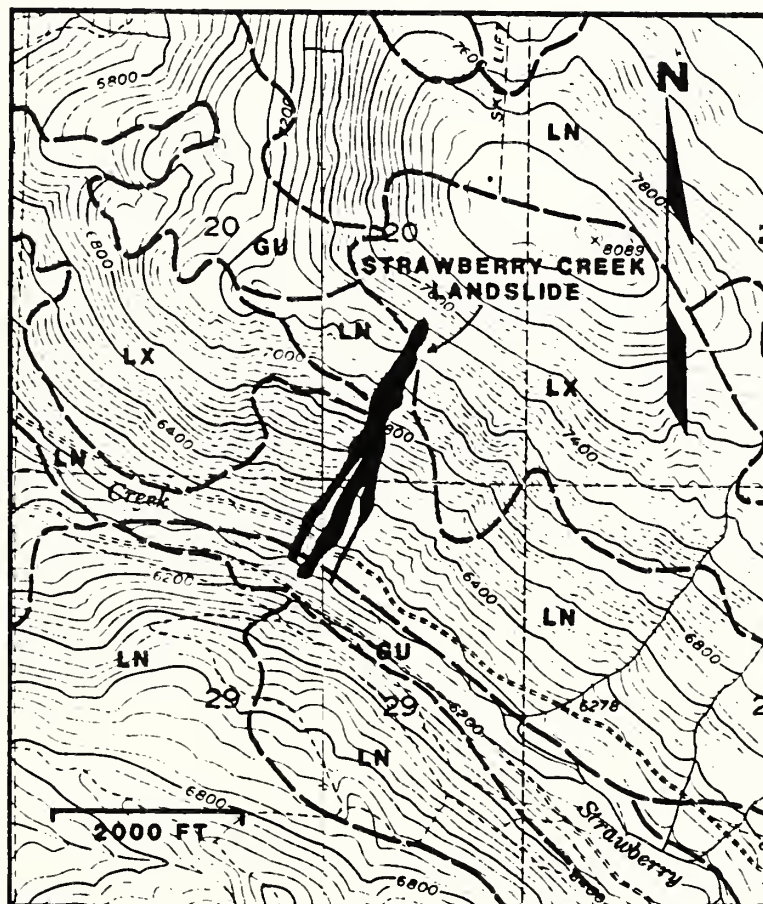
The soils in the study area have been mapped by Mitchell and Silverman (unpublished) primarily from aerial photographs at a scale of 1:15,840 and are presented at a scale of 1:24,000 (Fig. 10). The soils have been classified according to the system developed by the United States Department of Agriculture (1975). The soil map units of Mitchell and Silverman correlate closely to the surficial geologic units shown on Plate 1.

The soils on the lower section of the slope in the landslide vicinity are classified as Ledford-Notned complex, derived from weathered granitic rocks. A grain size distribution curve for sample 1, of Ledford-Notned soil, is presented in Appendix B, Graph 1. The Ledford-Notned complex soils are deep to very deep with weathered granitic bedrock typically occurring at depths between 40 and 60 inches. The soils are well drained to excessively drained, soil permeability is rapid to very rapid, and the maximum erosion hazard of the soil is moderate to high.

The soils located on the upper section of the mountain slope in the landslide vicinity are classified as Lithic Xerumbrepts-Rock outcrop complex, derived from weathered granitic rocks. A grain size distribution curve for sample 9, of Lithic Xerumbrepts soil, is



presented in Appendix B, Graph 2. The Lithic Xerumbrepts soils are shallow with hard rock typically occurring at depths ranging between 10 and 20 inches. The soils are excessively drained, the permeability of the soil is very rapid, and the maximum erosion hazard of the soil is very high. Runoff within rock outcrop areas is very high.



Soils Key: LX - Lithic Xerumbrepts-Rock outcrop complex  
 LN - Ledford-Notned complex  
 GU - Gerle-Umbrepts association

Figure 10. Soils Map of Strawberry Creek landslide vicinity from Mitchell and Silverman (unpublished).



The soils at the base of the slope near Strawberry Creek are classified as Gerle-Umbrepts association, derived from weathered glacial till, glacial outwash, and alluvium composed primarily of granitic rock. The Gerle soils are deep, typically developed 40 to 60 inches below the ground surface. The soils are well drained, soil permeability is moderately rapid, and the maximum erosion hazard of the soil is moderate.

### Landslide Morphology

The crown of the Strawberry Creek landslide is located at an elevation of 7,490 feet and the toe of the landslide deposit is located at an elevation of approximately 6,060 feet. The landslide travelled a horizontal distance of 3,125 feet and dropped 1,435 feet in elevation. The landslide deposit spreads out downslope to a maximum width of approximately 350 feet.

### Source Area

The source area of the Strawberry Creek landslide is located on a steep and relatively planar southwest-facing slope covered with dense brush and trees. A break-in-slope occurs in the source area at an elevation of approximately 7,400 feet. The slope within the immediate source area above 7,400 feet is approximately 37 degrees and below 7,400 feet is approximately 31 degrees.



Three relatively distinct scarps occur in the headscarp of the Strawberry Creek landslide. An initial scarp is located at an elevation of 7,400 feet. A secondary and tertiary scarp are located directly above the initial scarp at elevations of 7,450 feet and 7,490 feet, respectively.

The toe of the rupture surface of the initial debris-flow failure is located at an elevation of 7,280 feet. The base of the rupture surface of the initial failure is marked by a relatively planar surface on top of weathered granodioritic material. The rupture surface dips roughly parallel to the undisturbed ground surface at the margins of the landslide. The flanks of the initial failure are marked by lateral scarps ranging in height from about 3 feet near the toe of the rupture surface to 6 feet near the head. A subsurface profile of topsoil, colluvium, and weathered bedrock is exposed in the lateral scarps. Approximately 4 feet of dark brown, silty sand topsoil is underlain by approximately 2 feet of colluvium, containing angular granodiorite rock fragments. Highly-erodible weathered granodiorite bedrock underlies the topsoil and colluvium.

The initial failure is oblong-shaped (in plan view), and is approximately 130 feet wide and 220 feet long. The average depth of the rupture surface is approximately 5 feet below the former ground surface. An estimated 140,000 cubic feet of material, predominantly composed of residual soil and colluvium, was involved in the initial failure.



A large mound of debris containing fractured boulders, trees, and brush overlies the initial rupture surface (Fig. 11). The debris was derived from the secondary and tertiary failures, upslope from the initial failure.

The secondary scarp is marked by arcuate-shaped tension cracks in the ground surface, located at both sides of the landslide scarp at an elevation of approximately 7,450 feet. The margins of the scarp narrow significantly from an elevation of 7,400 to 7,450 feet. The tertiary scarp, which forms the crown of the landslide, is flanked by tension cracks at its margins. A large tension crack extends about 120 feet



Figure 11. Secondary and tertiary scarps in the crown of the Strawberry Creek landslide. Mound of debris derived from the secondary and tertiary failures is evident in foreground.



to the northwest from the landslide crown. The crack is as much as 1 foot wide with 2 to 3 feet of vertical downslope offset.

The vertical height of the lateral scarp increases dramatically above the initial failure, from 6 feet to approximately 50 feet at the crown of the headscarp. A topsoil layer, approximately 6 to 12 inches thick, is exposed in the secondary and tertiary scarps above the initial failure. The topsoil is underlain by colluvial material, 3 to 6 feet thick, which in turn is underlain by weathered and highly-erodible granodiorite bedrock. The headscarp above the initial failure is nearly vertical along its margins and decreases gradually to an angle of about 70 degrees at the crown.

Approximately 90,000 cubic feet of material, predominantly composed of weathered bedrock with minor amounts of colluvium and soil, was involved in the secondary and tertiary failures.

#### Zone of Deposition

Topsoil and colluvial materials were removed in an area of scoured ground located directly below the toe of the rupture surface.

Deposition of debris-flow material initiated at the margins of the landslide. Deposition also occurred as thin trails of debris within and extending from the area of scoured ground.

Two distinct deposits were laid down by the Strawberry Creek landslide: a brown debris-flow deposit associated with the initial failure, and a gray debris-flow deposit associated with the secondary and tertiary failures (Fig. 12). Exposures of brown debris-flow





Figure 12. Aerial photograph of the upper main channel of the Strawberry Creek landslide. Brown debris-flow deposit containing abundant fallen trees is evident at margins of landslide. Gray debris-flow deposit evident within the interior of the landslide contains large boulders and gullies. The large boulder in the foreground is 22 feet in diameter.

deposit are located along the margins of the upper debris-flow channel, the margins of the lower, central debris-flow channel, and within the two lower, outer debris-flow channels. Gray debris-flow deposit is confined to the interior of the upper debris-flow channel and to the interior of the lower, central debris-flow channel.



A rock outcrop of granodiorite (Fig. 13) is located in the center of the upper debris-flow channel at an elevation of approximately 6,960 feet. In general, the landslide uprooted every tree in its path, but below this rock outcrop several trees are still rooted in place. The trunks of the trees, however, are sheared off a few feet above their bases. The landslide mass was evidently travelling at a speed sufficient for the debris to become airborne as it flowed over the rock outcrop, snapping the tops of the trees off, while leaving their trunks firmly rooted.



Figure 13. Rock outcrop located within the center of the landslide channel. The debris flow became airborne as it passed over the outcrop and sheared off the tree tops below. Tree stumps are still rooted below the rock outcrop.



The upper debris-flow channel narrows slightly between 6,900 and 6,800 feet and then gradually widens downslope. At approximately 6,700 feet, the gray debris-flow deposit is confined to the center of the channel and relatively more brown debris-flow deposit is exposed. At approximately 6,500 feet, the landslide split into three separate flows, leaving undisturbed forest between the debris-flow channels.

A mound of brown debris-flow deposit, at approximately 6,400 feet in the eastern debris-flow channel, is located above a relatively undisturbed area containing upright trees. Apparently a portion of the flow lost energy and stopped in that area.

A large, rounded, bedrock boulder, 22 feet in diameter, is located within the gray debris-flow deposit at an elevation of 6,220 feet in the central debris-flow channel (Fig. 12). The boulder has clearly been displaced, possibly from the source area.

Debris from the three, lower debris-flow channels eroded the logging road located above Strawberry Creek before being deposited in the creek below. Debris from the central landslide channel was deposited 27 feet above the stream level on the opposite creek bank.

Stream action subsequent to the landslide event has created extensive gullies on the landslide surface, as evident on Figure 12. Water draining from the landslide has cut steep, v-shaped gullies through the debris-flow deposits, the underlying colluvium, and the weathered bedrock material to depths as much as 20 feet below the original landslide surface.



According to Kuehn and Bedrossian (1987), debris washed downstream from the Strawberry Creek landslide was responsible for filling the Pony Express Lake, which was created when the massive Highway 50 landslide, of April 9, 1983, blocked the South Fork of the American River about 5 miles west of Kyburz. Kuehn and Bedrossian (1987) indicate that the Strawberry Creek landslide contributed enough sediment to the American River to completely fill in Pony Express Lake, estimated to have been about 40 acre feet. This would have required over 1.7 million cubic feet of sediment. It was previously estimated that approximately 230,000 cubic feet of material failed from the source scars of the Strawberry Creek landslide. This estimate does not include the much larger volume of material which was scoured away by the debris flows along the landslide path downslope. It is reasonable that the total volume of debris which entered Strawberry Creek might be on the order of the amount of sediment estimated by Kuehn and Bedrossian to have filled Pony Express Lake.

### Landslide Deposits

Cross-sectional views of the debris-flow deposits are readily observed in the field where gullying processes have eroded through materials. The relationships of landslide deposits and underlying materials were also examined by excavating several pits using hand tools.



### Brown Debris-Flow Deposit

The brown debris-flow deposit forms significant levees up to 6 feet in height at the margins of the debris-flow channels. The marginal levees contain abundant organic debris and timber oriented subparallel to the direction of flow (Fig. 12). Trees within the deposit have commonly had their branches and bark removed. The thickness of the brown debris-flow deposit is irregular, averaging approximately 1 foot in depth towards the center of the debris-flow channels. The deposit commonly rests upon a scoured surface of colluvial or weathered bedrock material near the interior of the debris-flow channels. Near the margins of the landslide, the deposit commonly rests directly upon relatively undisturbed topsoil material.

Field Description: silty gravelly sand (SW), dark yellowish brown (10YR4/4), moist, slightly cohesive, angular rock fragments typically to 2 inches in length, contains approximately 10% cobbles and 5% boulders ranging in size to up to 7 feet in length, poorly-sorted texture lacking internal bedding, coarse-grained material heterogeneously distributed throughout fine-grained matrix, variable organic content composed of broken roots, wood fragments, and felled timber, ranging from approximately 5% in the interior of the debris-flow channels to up to 20% within the marginal levees of the deposit.



Grain Size: Samples 2 through 8 were collected from the brown debris-flow deposit at the locations shown on Plate 1, and were sieved in the laboratory. A grain size distribution curve representing the average grain size distribution for the seven samples is presented in Appendix B, Graph 3. The range of grain size distributions for the samples is included on the graph. The results of an hydrometer analysis performed on Sample 8 is also shown on Graph 3. The grain size analyses indicate that the brown debris-flow deposit contains the following percentages of materials:

gravel	- 18%	(> 2 mm)
sand	- 77%	(0.06 to 2 mm)
silt and clay	- 5%	(< 0.06 mm)

The sieve and hydrometer analyses indicate that the brown debris-flow deposit is relatively uniformly graded, contains minor silt-sized material, and is classified as a silty gravelly sand. The single hydrometer test performed on the brown debris-flow deposit indicates that it contains virtually no clay-sized material.

The brown debris-flow deposit is clearly associated with the initial failure of the Strawberry Creek landslide that occurred within the relatively deep soils of the Ledford-Notned complex soil unit. In-situ Ledford-Notned complex soil, sample 1, was collected from the location shown on Plate 1 at an elevation of 6,370 feet. A grain size distribution curve determined from sample 1 (Graph 1) falls within the range of grain size distributions for the brown debris-flow deposit shown on Graph 3.



## Gray Debris-Flow Deposit

The surface of the gray debris-flow deposit is irregular and lacks significant marginal levees. The deposit is up to 2 feet thick at the center of the flow and thins gradually towards the flow margins. The gray debris-flow deposit typically rests on top of the brown debris-flow deposit at the margins of the gray debris-flow deposit. At the interior of the debris-flow channel, the gray debris-flow deposit commonly rests upon the scoured surface of colluvial material.

Field Description: silty gravelly sand (SW), light gray (2.5Y7/2), moist, slightly cohesive, angular rock fragments typically to 3 inches in length, contains approximately 10% cobbles, 10% boulders ranging in size to 22 feet in length, poorly-sorted texture lacking internal bedding, coarse-grained material heterogeneously distributed throughout fine-grained matrix, approximately 1% organic debris composed of broken roots and wood fragments.

Grain Size: Samples 10 through 18 were collected from the gray debris-flow deposit at the locations shown on Plate 1, and sieved in the laboratory. A grain size distribution curve representing the average grain size distribution for the nine samples is presented in Appendix B, Graph 4. The range of grain size distributions for the samples is included on the graph. Hydrometer analyses were performed on samples 13, 14, and 18. The average grain size distribution curve and range for



the hydrometer analyses are shown on Graph 4. The grain size analyses indicate that the gray debris-flow deposit contains the following percentages of materials:

gravel	- 19%	(> 2 mm)
sand	- 74%	(0.06 to 2 mm)
silt and clay	- 7%	(< 0.06 mm)

The grain size analyses indicate that the gray debris-flow deposit is relatively uniformly graded, contains minor silt-sized material, and is classified as a silty gravelly sand. The hydrometer tests performed on the gray debris-flow deposit indicate it contains virtually no clay-sized material.

The gray debris-flow deposit is clearly associated with the secondary and tertiary failures of the Strawberry Creek landslide that occurred within the relatively shallow soils of the Lithic Xerumbrepts-Rock outcrop complex soil unit. Sample 9, of in-situ Lithic Xerumbrepts-Rock outcrop complex soil, was collected from the location shown on Plate 1 above the landslide headscarp. A grain size distribution curve determined from sample 9 (Graph 2) falls within the range of grain size distributions for the gray debris-flow deposit, shown on Graph 4.

#### Sequence of Deposition

A pit was excavated across a contact between the brown debris-flow deposit and the gray debris-flow deposit in the location shown on Plate 1, at an elevation of 6,210 feet. A similar contact is visible in Figure 12 at the margins of the landslide channel. The stratigraphic



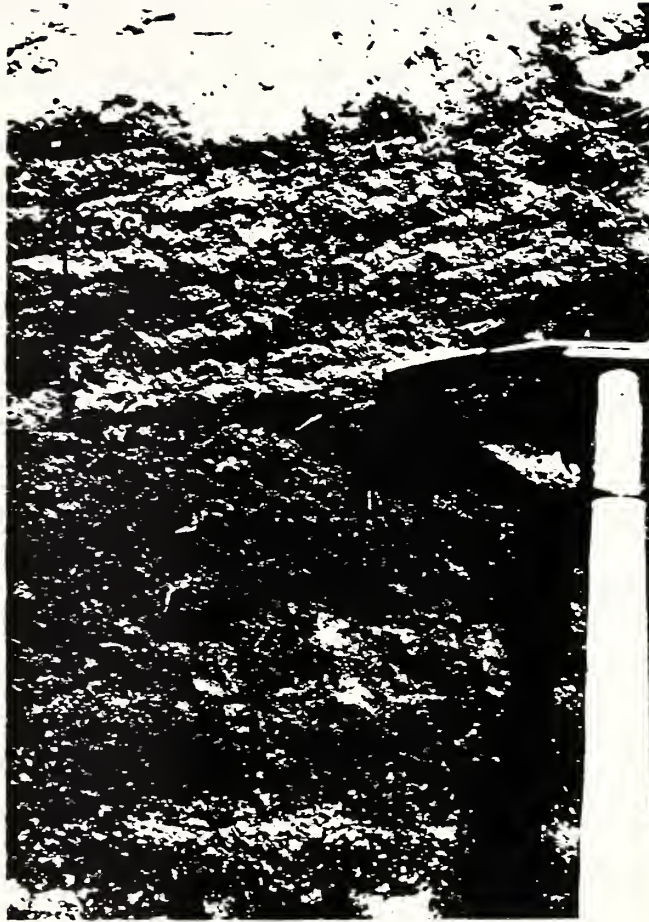


Figure 14. Relationships between gray debris-flow deposit (GDF), brown debris-flow deposit (BDF), and colluvium (COL) exposed on pit wall. Pick head points to contact between gray and brown debris-flow deposits.

relationship between the two deposits is illustrated in Figure 14, which shows a wall of the pit. The pick head points to the base of the gray debris-flow deposit which overlies brown debris-flow deposit. The brown debris-flow deposit rests upon a surface scoured on top of colluvial material, which is stained red from oxidation. Preexisting topsoil material on top of the colluvium had been removed by the erosive,



initial, debris-flow front as it travelled downslope. The relationships observed in the pit clearly indicate that the brown debris-flow deposit was laid down and subsequently covered by the gray debris-flow deposit.

A schematic cross-section perpendicular to the direction of flow of the landslide, shown as Figure 15, depicts the relationships of the landslide deposits. At locations towards the interior of the landslide channel, the gray debris-flow deposit commonly rests upon the scoured surface of colluvial or weathered bedrock material. This evidence indicates that the initial, brown debris-flow deposit was scoured away by the secondary, gray debris flow and incorporated into the gray debris flow.

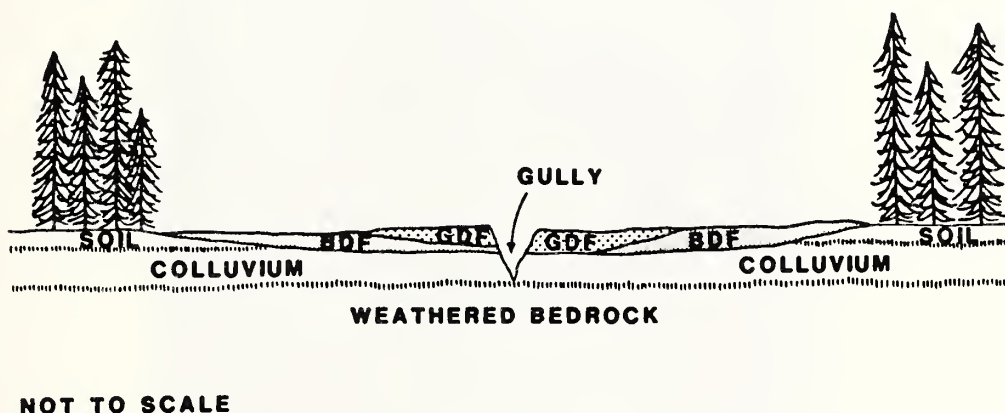


Figure 15. Schematic cross-section of the central Strawberry Creek landslide channel, perpendicular to flow direction, depicting the relationships of the brown and gray debris-flow deposits (BDF and GDF, respectively).



Failure Analysis and Reconstruction of Landsliding

An oblique aerial photograph taken about two weeks after the Strawberry Creek landslide event is shown in Figure 16. The photograph indicates that the snowline was very close to the source area of the landslide at the time of its failure. This snow level evidence, supported by temperature and stream level data presented in Figure 8,



Figure 16. Aerial photograph of the Strawberry Creek landslide (D. Totheroh) taken about two weeks after the landslide event. Note that the snowline is very near the source area of landslide.



suggests that groundwater levels were abnormally high within the source area preceding the landslide failure.

A significant break-in-slope occurs near the crown of the initial debris-flow failure of the Strawberry Creek landslide at an elevation of approximately 7,400 feet. The area above 7,400 feet has a slope angle of about 38 degrees and the area below 7,400 feet has a more gentle slope of about 30 degrees. Differences in vegetation and soil depth are associated with the break-in-slope. Soils are moderately deep (about 4 feet thick) and vegetation consists of dense forest below the break-in-slope. Above the break-in-slope, soils are thin (about 1 foot deep), rock outcrops are abundant, and dense brush predominates. Soils above the break-in-slope are also relatively more permeable and have a higher erosion hazard than soils below the break-in-slope (Mitchell and Silverman, unpublished).

Groundwater conditions near the source area of the landslide also appear to be influenced or controlled by the break-in-slope and soil conditions. Several springs located within the landslide scar and at its margins, at an elevation of approximately 7,270 feet, indicate that groundwater draining from the steeper slope above accumulates and surfaces below the break-in-slope within the less permeable and deeper soils. The location of the springs, directly below the toe of the initial debris-flow rupture surface, suggests that spring activity may have contributed to triggering the initial failure.

The initial debris-flow failure of the Strawberry Creek landslide occurred directly above the springs within relatively deeper soil and colluvium located below the break-in-slope. The initial debris-flow



failure was likely triggered by rising groundwater levels. A perched water table probably developed on top of the interface between the relatively impermeable weathered bedrock and the permeable overlying soil and colluvium due to rapidly melting snow. At a critical groundwater level, the shallow layer of soil and colluvium began to slip, and mobilized as a rapid debris flow.

The initial debris flow scoured away and incorporated soil, colluvium, and timber and laid down the brown debris-flow deposit as it progressed downslope. The flow spread out gradually until it reached a minor topographic bench located at an elevation of approximately 6,800 feet. The decrease in slope at the bench may have caused the flow to decelerate, spread out, and separate into three distinct flows at an elevation of 6,500 feet. Each of the three flows scoured through the logging road above Strawberry Creek and then came to rest in the creek at the base of the slope.

At some time after the initial failure, possibly a matter of seconds or several hours, the secondary and tertiary debris-flow failures occurred along the two distinct scarps located above the initial scarp. Because the secondary and tertiary failures involved similar materials, only one deposit related to the failures, the gray debris-flow deposit, can be clearly distinguished. The time period between the secondary and tertiary failures also may have been a matter of seconds or several hours. The failures probably mobilized due to a combination of high groundwater levels and undermining or removal of lateral support resulting from the initial failure.



The secondary and tertiary debris-flow failures occurred within highly-erodible weathered granodiorite bedrock material covered by a thin veneer of soil and colluvium. The flows carried granodiorite boulders, possibly up to 22 feet in diameter, downslope and laid down the gray debris-flow deposit. The gray debris flow deposited material on top of the brown debris-flow deposit or commonly scoured away and incorporated previously deposited brown debris-flow material. The gray debris flow travelled down the central, lower, flow channel (initially cut by the brown debris flow) before coming to rest in Strawberry Creek at the base of the slope.

Debris from the landslide created a temporary dam in Strawberry Creek (Kuehn and Bedrossian, 1987) which had washed downstream by the day after the landslide. Steady streams of water also were flowing down each of the three debris-flow channels the day after the failure. The streams rapidly cut through the debris-flow deposits and underlying weathered bedrock, creating deeply incised gullies.

Local woodcutters removed much of the fallen timber from the toe area of the Strawberry Creek landslide shortly after its failure. The damaged logging road was subsequently repaired by placing culverts across each of the three landslide flow channels and regrading the road. Standing timber located in the undisturbed areas within the landslide boundaries has recently been harvested.



## PYRAMID GUARD STATION LANDSLIDE

Late in the afternoon on June 4, 1983, Dick White, of the California Highway Patrol was driving west on U.S. Highway 50. The highway was flooded by about a foot of water and debris approximately 1/2 mile west of Pyramid Guard Station. The water and debris had overtopped a culvert serving a perennial creek draining the mountain slope above the road. Patrolman White proceeded through the flooded area and blocked traffic on the west side of the drainage. He then drove back through the flooded zone and proceeded east to stop traffic coming from the opposite direction. Patrolman White had travelled a few hundred feet east, past the flooded drainage, when he saw in front of him what he described as "a big hellacious wall of mud carrying large trees and boulders across the road". The wall of mud and debris was higher than the top of his patrol car. The patrolman witnessed the initial debris-flow front of the Pyramid Guard Station landslide, shown on Figure 17 and on Plate 2. After the main body of the debris flow passed over the road, water and debris continued to flow in minor surges down the channel for the rest of the afternoon. The highway was closed for about a day as a crew cleared debris from the road, according to Terry Rogers of the California Department of Transportation. The debris flow did not significantly damage the road pavement.





Figure 17. Aerial photograph of the Pyramid Guard Station landslide looking towards the north. The landslide is evident as a sinuous scar in the center of the photo near the right margin of the Wright's Fire burned area. U.S. Highway 50 is located in the foreground at the base of slope, above the South Fork of the American River. Snow-covered peaks of the Sierra Nevada crest are evident in the background.



The Pyramid Guard Station landslide initiated as a shallow soil slip within a small swale on the upper section of the mountain slope forming the northern side of the American River canyon. The crown of the landslide is located at an elevation of 7,500 feet.

The soil slip developed into a rapid debris flow which travelled through a small stand of trees, scraping the bark from the base of the trees. The debris flow accelerated down a previously unchannelled slope and entered the drainage of an intermittent creek. The debris flow collected additional debris and water from the creek bottom as it moved down the channel. The debris flow frequently overtopped the creek banks leaving a debris-flow deposit along the margins of the creek. The landslide destroyed a series of rock check dams constructed above U.S. Highway 50 and then deposited debris onto the highway. The flow continued down the creek below the highway and ultimately deposited debris in the South Fork of the American River.

### Physical Setting

#### Slope

The Pyramid Guard Station landslide is located on a southwest-facing mountain slope with an average gradient of approximately 18 degrees from the ridgetop above, to the American River at its base. The landslide headscarp is located within the center of a small swale flanked by minor bedrock ridges. A relatively flat glaciated surface at the top of the slope is located at an elevation of approximately 7,700



feet, 200 feet above the landslide crown. The South Fork of the American River is located at the base of the landslide at an elevation of approximately 5,300 feet.

Slope Profile B-B', shown on Plate 3, depicts the slope from the ridgetop to the headscarp of the landslide. The profile extends, as a stream profile, through the headscarp of the landslide and its flow channel, to the base of the landslide at the South Fork of the American River. The upper section of the slope profile, from an elevation of approximately 7,600 to 6,400 feet, is a relatively even slope with an average gradient of about 26 degrees. Between 6,400 feet and 5,600 feet, the slope profile has a concave shape with an average gradient of 15 degrees. The slope profile is convex from 5,600 feet to the base of the profile at 5,300 feet with an average gradient of 9 degrees.

#### Vegetation

The natural vegetation on the upper part of the mountain slope is primarily brush with sparse stands of mixed noncommercial conifer timber. The lower portion of the slope below approximately 5,800 feet is more densely forested with conifer.



## Surface Water

No evidence of spring activity was observed in the immediate vicinity of the landslide source area at the time of the field investigation, during 1985. A spring, however, is located at the head of the intermittent creek to the east of the source area.

## Site History

No clear evidence of recent landsliding in the vicinity of the source area was detected during a review of several sets of aerial photograph stereo pairs dating from 1965, 1966, 1973, and 1980. A list of the aerial photographs reviewed is presented in Appendix A. No evidence of any preexisting spring or stream activity within or immediately below the source area was observed on the aerial photographs.

## 1981 Wildfire

During August of 1981, a wildfire, referred to as the Wright's Fire, occurred on the mountain slope above and to the west of Pyramid Guard Station. The burned area is evident as a barren area in the photograph shown on Figure 17. The fire burned 3,600 acres, removing most of the vegetation on the brush-covered areas. Ground-cover in forested areas was burned and trees were badly scorched, although they were typically left standing. In October of 1981, the U.S. Forest



Service seeded the area affected by the Wright's Fire. Noncommercial timber and brush areas were seeded with both annual rye and orchard grass, whereas areas of commercial timber were only seeded with annual rye (Kuehn, 1985).

#### 1982 Thunderstorm

On June 18, 1982, a thunderstorm of record intensity occurred over the area burned by the Wright's Fire the previous year. A tipping bucket rain gauge located at Alpha site (Fig. 3), operated by the Sacramento Municipal Utilities District, recorded the event. According to Goodridge (1982), a rainfall rate of 1.81 inches in 6 minutes was registered during the height of the storm. Kershner (1983) estimates that 5 to 7 inches of rain fell during a 1 hour period. The rainfall event was the most intense ever officially recorded in the Sierra Nevada.

#### 1982 Debris Torrent

The thunderstorm of June 18, 1982, caused extensive erosion within the 220-acre watershed above Pyramid Guard Station. Excessive runoff from the thunderstorm event triggered a debris flow within the watershed drainage.

There was no evidence of a discreet landslide failure or scarp associated with the 1982 debris-flow event. Instead, the debris flow apparently was initiated by the intensive sheet-wash which occurred on



the mountain slopes. Massive quantities of water and granular debris were subsequently introduced into the watershed channel. The 1981 wildfire probably contributed to the amount of erosion occurring in the storm by removing vegetation on the slopes that acts in stabilizing surficial soil materials. Unstable material within the bottom of the drainage channel was mobilized to produce a rapid, channellized debris flow. The debris flow was similar to events described by VanDine (1985) as "debris torrents," wherein unstable debris within a channel bottom typically is mobilized by an extreme water discharge.

The landslide temporarily closed U.S. Highway 50 as it deposited approximately 5,000 cubic yards of sediment (Kuehn, 1985) onto the road on June 18, 1982. The debris torrent continued down the drainage until it entered the South Fork of the American River. The debris torrent typically overtopped the drainage channel, laying down a thin debris-flow deposit along the margins of the channel.

The 1982 debris torrent severely eroded the drainage channel, producing steep and unstable, v-shaped side walls prone to erosion. The U.S. Forest Service constructed a series of rock check dams within the channel above the highway in an attempt to stabilize the channel and protect the highway from potential future inundation.

#### Older Landslides

Field evidence indicates that debris-flow landsliding has been a recurrent event within the watershed containing the Pyramid Guard Station landslide. The large bowl at the head of the main watershed



drainage channel, to the east of the source area of the Pyramid Guard Station landslide, contains several partially revegetated soil-slip scars. The bark along the uphill sides of the bases of several trees located in a small stand below one of the scars, apparently, has been scraped away by debris which flowed around the trees (Fig. 18).



Figure 18. Tree bark along the bases of several trees was probably removed by a previous debris-flow event. Trees are located in bowl to the east of the source area of the Pyramid Guard Station landslide.

The slope immediately above Pyramid Guard Station and U.S. Highway 50 (Plate 2) has a distinctive fan shape suggestive of a depositional zone formed by previous debris flows. An old abandoned section of the drainage channel between the elevations of 5,950 and 5,700 feet (Fig. 19) suggests that the channel was blocked by past debris-flow activity.





Figure 19. Aerial photograph of deeply-incised Pyramid Guard Station drainage channel at an elevation of 5,990 feet. Active channel is to left of the photograph and older abandoned channel to the right. The direction of flow is from top to bottom of the photograph.

An exposure in a steeply undercut stream-bank, located at an elevation of 5,605 feet (Plate 2) is shown in Figure 20. The materials exposed in the stream-bank have been uncovered by the recent debris-flow events and subsequent stream erosion. The exposure reveals a series of three, older debris-flow deposits, units A through C, which are



described in detail in Figure 20. The 1983 debris-flow deposit, not shown in Figure 20, overlies the undercut exposure. An older stream-flow deposit, unit D, underlies the older debris-flow deposits. There is no evidence of the 1982 debris-torrent event in the exposure.

The debris-flow deposits vary in thickness from 0.75 to 1.5 feet. The contacts between units A and B, and between units C and D, respectively, are relatively sharp erosional contacts. The contact between units B and C is less sharp but is defined by changes in color and texture. All of the deposits in the exposure have a very fresh appearance and lack evidence of soil development. The textures of the deposits range from sandy silt to gravelly sand with variable rock fragment content. Rock fragments are granodioritic in composition, are subangular to subrounded, and reach 2 feet in length.

The two, lower debris-flow deposits contain organic material, such as charcoal, wood fragments, and pine cones. The wood fragments and pine cones appear relatively fresh and uncompacted, and have undergone very little decomposition. Samples of charcoal were collected from the locations shown on Figure 20 from units B and C. The samples were dated by the U.S. Geological Survey Radiocarbon Laboratory in Menlo Park, California.

The sample taken from unit C yielded an age of  $2085 \pm 40$  y.b.p. (years before present, U.S.G.S. 2297). The charcoal sample from the overlying debris-flow deposit, unit B, yielded an age of  $1770 \pm 180$  y.b.p. (U.S.G.S. 2296). These dates suggest a recurrence interval between the successive debris flows of 315 years.





#### Unit Descriptions

- Unit A : gravelly sand, light gray (10YR7/2), dry, minor silt, cobbles, and boulders, subangular to subrounded gravel clasts and rock fragments to 2 feet in length, upward-coarsening sequence, OLDER DEBRIS-FLOW DEPOSIT
- Unit B : silty sand, light olive gray (5Y6/2), dry, minor gravel and charcoal fragments, radiocarbon date of 1770 y.b.p., OLDER DEBRIS-FLOW DEPOSIT
- Unit C : sandy silt, dark gray (5Y4/1), dry, abundant wood and charcoal fragments and small pine cones, radiocarbon date of 2085 y.b.p., OLDER DEBRIS-FLOW DEPOSIT
- Unit D : sandy gravel, white (10YR8/2), dry, minor silt, rounded cobbles and boulders to 1 foot, faint stratification, subhorizontal reddish iron-oxide staining along strata, STREAM-FLOW DEPOSIT

Figure 20. Undercut stream-bank exposure. Three, older debris-flow deposits, units A through C, are underlain by a stream-flow deposit, unit D. Soil pick is about 1 foot long.



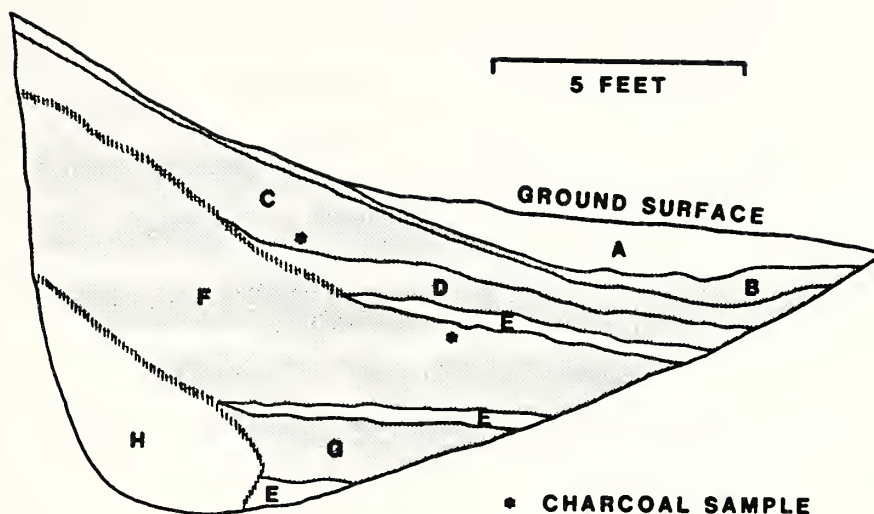
A backhoe was utilized to excavate a trench into the bank of the drainage channel just above the highway at an elevation of 5,555 feet (Plate 2). The trench was approximately 17 feet in length with a maximum depth of 9 feet. The trench exposed a series of interlayered stream-flow deposits and debris-flow deposits, generally pinching out or thinning away from the channel center. A detailed log of the trench is presented in Figure 21.

A highly weathered granitic boulder, unit H, was located at the bottom of the trench. Four distinct stream-flow deposits, all classified for simplicity as unit E, were observed in the trench. The stream-flow deposits are composed of clean and sorted, gravelly sand containing very few fines. Five distinct debris-flow deposits, units B, C, D, F, and G, consist of poorly-sorted, sandy silt or silty sand.

There was no evidence of the 1982 debris-torrent event in the trench, however, the uppermost debris-flow deposit, unit B, was clearly from the 1983 debris-flow event. The 1983 debris-flow deposit had recently been partially eroded and buried by subsequent stream-flow activity, unit A. A similar sequence was evident in two of the underlying older debris-flow deposits, units F and G, which had also been covered by later stream-flow deposits, unit E.

Charcoal samples from two of the older debris-flow deposits in the trench, units C and F, were dated  $110 \pm 50$  y.b.p. (U.S.G.S. 2298) and  $325 \pm 45$  y.b.p. (U.S.G.S. 2299), respectively. The radiocarbon dates indicate that, at a minimum, five debris-flow events have occurred in the Pyramid Guard Station drainage in the last 325 years; unit F, the 325 year old deposit; unit C, the 110 year old deposit; unit D, the





#### Unit Descriptions

- Unit A : gravelly sand, light gray (10YR6/1), moist, clean and sorted, faint stratification and heavy-mineral concentrations, rounded gravel clasts, channelled contact with underlying unit, ACTIVE STREAM-FLOW DEPOSIT
- Unit B : gravelly sandy silt, very dark grayish brown (10YR3/2), very moist, poorly-sorted, no stratification, minor charcoal and wood fragments, base of unit marked by 1/4- to 1/2-inch thick mat of slightly decomposed pine needles, 1983 DEBRIS-FLOW DEPOSIT
- Unit C : gravelly sandy silt, dark yellowish brown (10YR4/4), moist, poorly-sorted, minor roots and charcoal fragments, base of unit marked by faint layer of decomposed organics, radiocarbon date of 110 y.b.p., OLDER DEBRIS-FLOW DEPOSIT
- Unit D : sandy clayey silt, brownish yellow (10YR5/4), moist, poorly-sorted, friable and loose, minor charcoal fragments, OLDER DEBRIS-FLOW DEPOSIT
- Unit E : gravelly sand, very pale brown (10YR7/3), moist, clean and sorted, no organics or charcoal fragments, OLDER STREAM-FLOW DEPOSIT
- Unit F : sandy clayey silt, brownish yellow (10YR6/8), slightly moist, poorly-sorted, abundant roots, very loose, radiocarbon date of 325 y.b.p., OLDER DEBRIS-FLOW DEPOSIT
- Unit G : gravelly sandy silt, yellowish brown (10YR5/4), slightly moist, poorly-sorted, OLDER DEBRIS-FLOW DEPOSIT
- Unit H : gravelly sand, yellowish brown (10YR5/6), slightly moist, relic crystalline texture, subangular oxidized clasts of quartz, plagioclase and hornblende, DECOMPOSED GRANITIC BOULDER

Figure 21. Log of backhoe trench.



undated intervening deposit; the 1982 debris-torrent deposit; and unit B, the 1983 deposit. In addition, the two older debris-flow events recorded in the undercut stream-bank, higher up the drainage, occurred within a 316 year interval. The relatively recent debris-flow events and the older debris-flow events are listed in Table 1.

TABLE 1 - PYRAMID GUARD STATION DEBRIS-FLOW EVENTS

Recent Debris-Flow Events

1983 Pyramid Guard Station  
 1982 Debris Torrent  
 110 + or - 50 y.b.p.  
 undated intervening deposit  
 325 + or - 45 y.b.p.

Older Debris-Flow Events

1770 + or - 180 y.b.p.  
 2086 + or - 40 y.b.p.

There may have been more intervening debris-flow events that were not recorded at the undercut stream-bank location or at the backhoe trench location. For example, the 1982 debris-torrent event was not recorded at either of those locations, yet, deposits from the 1982 debris-torrent event are clearly evident underlying the 1983 debris-flow deposit in several hand-dug pits located along the channel margins.



## Site Geology

### Bedrock Geology

The Pyramid Guard Station landslide is underlain by bedrock mapped and described by Loomis (1981) as the Wrights Lake Granodiorite (Fig. 4), a large intrusive body covering about 300 square miles. Loomis mapped steeply dipping to vertical bedrock foliations varying in strike from north to northwest in the vicinity of the landslide. Everden and Kistler (1970) have measured Cretaceous radiometric ages of 92.8 m.y., 97.6 m.y., and 102 m.y. for the Wrights Lake Granodiorite.

### Surficial Geology

Generalized units of surficial geology in the vicinity of the Pyramid Guard Station landslide are delineated on Plate 2. Surface material along the ridgeline to the east of the landslide has been mapped as bedrock. Bedrock units are mapped along the ridge to the west of the landslide, to either side of the source area, and above the source area. A large bedrock unit is located below the highway to the east of the landslide. Surficial materials in the remaining areas, within swales and along minor drainages, have been mapped as soil and colluvium. Recent alluvium has been mapped within the drainage of the South Fork of the American River.



## Soils

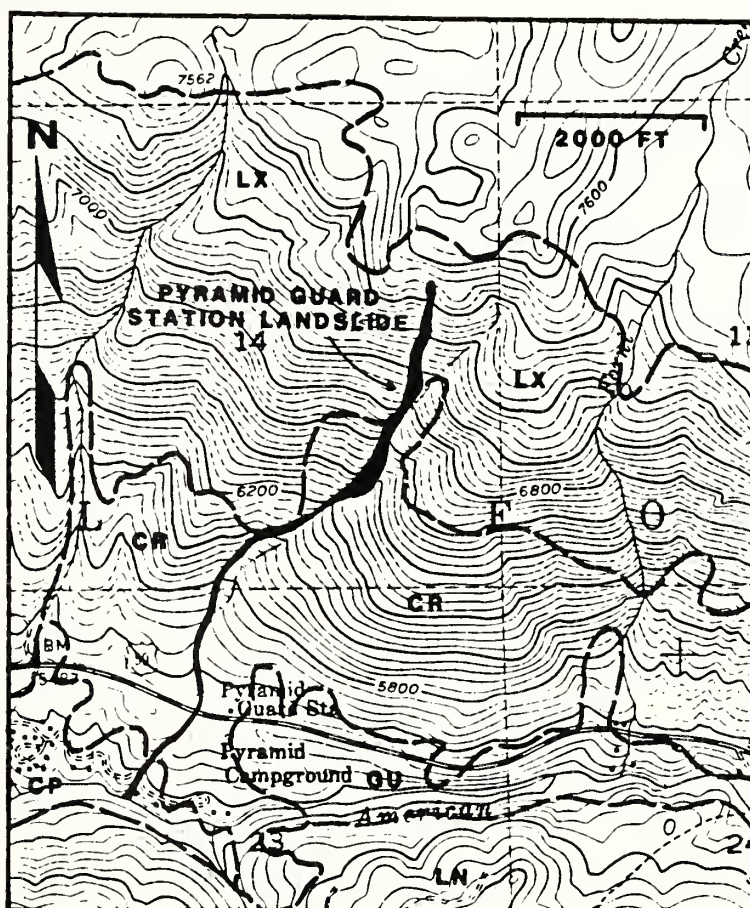
The soils in the Pyramid Guard Station study area have been mapped by Mitchell and Silverman (unpublished), primarily from aerial photographs at a scale of 1:15,840, and are presented at a scale of 1:24,000 (Fig. 22). The soils have been classified according to the system developed by the United States Department of Agriculture (1975).

The soils located on the upper section of the mountain slope in the vicinity of the Pyramid Guard Station landslide are classified as Lithic Xerumbrepts-Rock outcrop complex, derived from weathered granitic rocks. Grain size distribution curves for samples 1 and 7, of Lithic Xerumbrepts soil, are presented in Appendix B, Graphs 5 and 6. The Lithic Xerumbrepts soils are shallow, with hard rock typically occurring at depths ranging from 10 to 20 inches. The soils are excessively drained, the permeability of the soil is moderately rapid, and runoff is very rapid. The maximum erosion hazard of the unit is very high.

The soils on the lower section of the slope are classified as Chaix-Rock outcrop complex, derived from weathered granitic rock. The Chaix soils are moderately deep, with weathered granitic rock typically occurring at depths ranging from 20 to 40 inches. The soils are excessively drained, the permeability of the soil is moderately rapid, and its maximum erosion hazard is very high. Runoff on rock outcrop areas is very rapid.

The soils at the base of the slope within the American River drainage are classified as Chaix-Pilliken coarse sandy loams, derived from weathered granitic rock. The Chaix-Pilliken soils are moderately





Soils Key: LX - Lithic Xerumbrepts-Rock outcrop complex  
 CR - Chaix-Rock outcrop complex  
 CP - Chaix-Pilliken coarse sandy loams  
 LN - Ledford-Notned complex

Figure 22. Soil map of Pyramid Guard Station landslide vicinity, Mitchell and Silverman (unpublished).

deep to deep, with highly weathered granitic rock typically occurring at depths ranging from 40 to 60 inches. The soils are well drained to excessively drained. The permeability of the soils is moderately rapid and its maximum erosion hazard is moderate.



## Landslide Morphology

The crown of the Pyramid Guard Station landslide is located at an elevation of 7,500 feet and the toe of the landslide is located at 5,300 feet. The landslide travelled a horizontal distance of 6,875 feet and dropped 2,200 feet in elevation. The maximum width of the landslide deposit is approximately 160 feet.

### Source Area

The source area of the Pyramid Guard Station landslide is located within a broad swale between two bedrock ridges. The source area slopes toward the southwest at approximately 26 degrees. Two distinct scarps are evident within the source area (Fig. 23). The head of an initial scarp is located at an elevation of 7,490 feet and a secondary scarp is located at 7,500 feet, to the west and adjacent to the initial scarp. A linear scarp that forms the eastern edge of the secondary scarp extends down from the crown towards the center of the source scar as shown on Plate 2. The secondary scarp clearly cuts across the initial scarp.

The toe of the rupture surface of the initial debris-flow failure is located at an elevation of 7,445 feet. The initial rupture surface is relatively planar and dips roughly parallel to the original ground surface. The rupture surface occurs within a black silty sand topsoil material which is exposed within the lateral scarps. The lateral scarp along the eastern margin of the initial failure ranges in height from 3 feet at its base to 5 feet at the crown.





Figure 23. Aerial photograph of the Pyramid Guard Station landslide source area. Darker-colored soil material is evident in the source scar of the initial failure covered by tree shadows. Lighter-colored colluvial and bedrock materials are evident in the source scar of the secondary failure towards the bottom center of the photo.

The initial failure has a tear-drop shape (in plan view), and is approximately 80 feet long and 40 feet wide with an average depth of about 4 feet. The initial failure involved an estimated 11,000 cubic feet of material, predominantly composed of residual soil.

The secondary failure occurred along the western margin of the initial failure. Its rupture surface is irregular and occurs within rocky colluvial and weathered bedrock material. The western marginal scarp of the secondary failure ranges in height from approximately 4 feet near the toe of the rupture surface to 12 feet at the crown. Residual soil, with a depth of approximately 3 feet, occurs within the



marginal scarp. The residual soil is underlain by colluvial and weathered bedrock material containing subangular granodiorite boulders up to 10 feet in length.

The secondary failure also has a teardrop shape, approximately 100 feet long and 30 feet in width, with an average depth of about 6 feet. An estimated 12,000 cubic feet of material, predominantly composed of colluvium and weathered bedrock, was involved in the secondary failure.

### Zone of Deposition

Debris-flow material was initially deposited directly below the toe of the rupture surface. Two distinct deposits were laid down along the upper portion of the Pyramid Guard Station landslide: a brown debris-flow deposit associated with the initial failure, and a gray debris-flow deposit associated with the secondary failure. An undifferentiated debris-flow deposit was laid down along the lower portion of the landslide.

A small stand of trees located directly below the toe of the rupture surface remained relatively undisturbed by the debris-flow events. However, landslide debris flowing around the trees removed bark from the uphill sides of the trees as shown on Figure 24. The damage to the tree trunks is similar to that observed to trees, shown in Figure 18, located below an older soil-slip scar to the east of the source area. The debris flow left mud lines along the trees, shown in Figure 24, up to 4 feet above the ground level. Splattered mud marks are



evident on the trees up to 15 feet above ground level. Small piles of debris remain along the uphill edge of the trees.

The hillslope immediately below the source area was examined in a review of aerial photographs taken prior to the landslide event. The hillslope was relatively smooth and lacked any notable channelling. The relatively smooth even slope, consequently, did not restrict the debris flow, which spread out significantly as it travelled downslope.

Exposures of brown debris-flow deposit are located at the margins of the landslide, from just below the source area down to an elevation of 6,880 feet. Exposures of gray debris-flow deposit are located within the interior of the landslide down to the same elevation. A narrow gully flanked by rock outcrops is located at an elevation of 6,880 feet. Below the gully, the gray and brown debris-flow deposits cannot be distinguished and the debris-flow material is mapped as undifferentiated debris-flow deposit.

Below the gully, deposits of the undifferentiated debris-flow material generally are confined to the drainage channel and to narrow deposits along the margins of the channel. The flow spreads out significantly at approximately 6,400 feet, above a bend in the channel where it is joined by another drainage channel originating from a large bowl to the east of the source area.

The deposit is typically confined to the drainage channel below the creek junction. At 5,990 feet, the deposit widens at another bend in the channel near the top of an older abandoned channel located to the east of the active channel (Fig. 19). Below 5,930 feet, the deposit is generally confined to the drainage channel.





Figure 24. Bark removed from trees located just below the toe of the rupture surface of the Pyramid Guard Station landslide. The bedrock boulder adjacent to the tree has been transported by the debris flow. Day pack 18 inches tall.

The debris flow destroyed a series of rock check dams located between the highway and an elevation of 5,630 feet. Material from the debris flow and material from subsequent surging was deposited onto the highway. The majority of the debris-flow material, however, continued over the highway, remaining within the drainage below. The debris flow covered a gravel road crossing the drainage just above the South Fork of the American River before it was deposited into the river. Rock debris from the check dams is evident in the channel of the South Fork of the American River.



The debris-flow front collected unstable debris from the channel bottom and severely eroded the channel bottom and creek banks as it progressed. Stream action subsequent to the landslide event has severely gullied and eroded the drainage. Undercut stream banks along the drainage have commonly sloughed into the stream channel.

### Landslide Deposits

Cross-sectional views of the debris-flow deposits are readily observed in the field where gullies have been cut through materials. The relationships of landslide deposits and underlying materials were also examined in a trench excavated with a backhoe. Several pits were also excavated using hand tools.

#### Brown Debris-Flow Deposit

The brown debris-flow deposit has an average width of about 125 feet and is a relatively thin deposit ranging in thickness from about 3 to 6 inches. The surface of the deposit is relatively even, lacking marginal levees. The deposit typically conforms to the previous ground surface and rests upon topsoil and vegetation.



Field Description: silty gravelly sand (SW), very dark grayish brown (2.5Y3/1) to black (10YR2/1), moist, very minor amounts of clay, subrounded gravel to 1 inch, approximately 5% subangular cobble- and boulder-sized material, poorly-sorted texture lacking internal bedding, coarse-grained material heterogeneously distributed throughout fine-grained matrix, approximately 1% organic material composed of broken roots and minor wood fragments

Grain Size: Samples 2 through 6 were collected from the brown debris-flow deposit at the locations shown on Plate 2, and sieved in the laboratory. A grain size distribution curve representing the average grain size distribution for the five samples is presented in Appendix B, Graph 7. The range of grain size distributions for the samples is included on the graph. The average curve indicates that the brown debris-flow deposit contains the following percentages of materials:

gravel	-	18%	(> 2 mm)
sand	-	78%	(0.06 to 2 mm)
silt and clay	-	4%	(< 0.06 mm)

The sieve analyses indicate that the brown debris-flow deposit is relatively uniformly graded, contains minor silt-sized material, and is classified as a silty gravelly sand. The projected trend of the curve indicates that the brown debris-flow deposit contains very little clay-sized material.



The brown debris-flow deposit is clearly associated with the initial failure scar. In-situ soil material, sample 1, was collected from the location above the initial failure scar shown on Plate 2. A grain size distribution curve determined for sample 1 (Graph 5) falls within the range of grain size distributions for the brown debris-flow deposit shown on Graph 7.

#### Gray Debris-Flow Deposit

The gray debris-flow deposit has an average width of about 30 feet, varies in thickness from approximately 1/2 to 1 foot towards the interior of the flow, and thins at the flow margins. The surface of the flow is irregular and lacks marginal levees. Near the center of the flow, the deposit typically rests on a scoured surface on top of topsoil or colluvial material. Towards the flow margins, the deposit rests upon the initial, brown debris-flow deposit.

Field Description: silty gravelly sand (SW), light gray (10YR6/1), slightly moist, very minor clay, subangular to subrounded rock fragments to 2 inches, approximately 10% cobbles, 5% boulders, cobbles and boulders typically subangular, up to 10 feet in length, poorly-sorted texture lacking internal bedding, coarse-grained material heterogeneously distributed throughout fine-grained matrix, minor organic material composed of broken roots and wood fragments



Grain Size: Samples 8 through 12 were collected from the gray debris-flow deposit at the locations shown on Plate 2, and sieved in the laboratory. A grain size distribution curve representing the average grain size distribution for the five samples is presented in Appendix B, Graph 8. The range of grain size distributions for the samples is included on the graph. The average curve indicates that the gray debris-flow deposit contains the following percentages of materials:

gravel	- 21%	(> 2 mm)
sand	- 75%	(0.06 to 2 mm)
silt and clay	- 4%	(< 0.06 mm)

The sieve analyses indicate that the gray debris-flow deposit is relatively uniformly graded, contains minor silt-sized material, and is classified as a silty gravelly sand. The projected trend of the curve indicates that the gray debris-flow deposit contains very little clay-sized material.

The gray debris-flow deposit is clearly associated with the secondary failure scar. In-situ soil material, sample 7, was collected from the location above the secondary failure scar shown on Plate 2. A grain size distribution curve determined for sample 7 (Graph 6) falls within the range of grain size distributions for the gray debris-flow deposit.



## Undifferentiated Debris-Flow Deposit

The undifferentiated debris-flow deposit has a variable width and variable thickness which generally does not exceed 1.5 feet. The debris-flow deposit has an irregular surface and is typically exposed along the drainage channel margins (Fig. 25). Irregular and discontinuous marginal levees up to 1 foot high occur at locations along the edges of the deposit. In general, however, the deposit lacks marginal levees. The deposit typically rests upon a scoured surface cut into topsoil or colluvial material.

Field Description: silty gravelly sand (SW), light gray (10YR6/1), slightly moist, very minor amounts of clay, subangular to rounded rock fragments typically to 2 inches, approximately 15% cobbles and 5% boulders to 7 feet in length, poorly-sorted texture lacking internal bedding, coarse-grained material heterogeneously distributed throughout fine-grained matrix, minor organic material composed of broken roots and wood fragments, deposit is commonly underlain by thin mat of pine needles in forested areas

Grain Size: Samples 13 through 17 were collected from the undifferentiated debris-flow deposit at the locations shown on Plate 2, and sieved in the laboratory. A grain size distribution curve representing the average grain size distribution of the five samples is presented in Appendix B, Graph 9. The range of grain size distributions





Figure 25. Exposure of undifferentiated debris-flow deposit on topsoil material located upslope from U.S. Highway 50.

for the samples is included on the graph. The average curve indicates that the undifferentiated debris-flow deposit contains the following percentages of materials:

gravel	-	28%	( $> 2$ mm)
sand	-	68%	( $0.06$ to $2$ mm)
silt and clay	-	4%	( $< 0.06$ mm)



The sieve analyses indicate that the undifferentiated debris-flow deposit is relatively uniformly graded, contains minor silt-sized material, and is classified as a silty gravelly sand. The projected trend of the curve indicates that the undifferentiated debris-flow deposit contains very little clay-sized material.

The undifferentiated debris-flow deposit is more coarse-grained than the brown and gray debris-flow deposits. The undifferentiated debris-flow deposit is likely more coarse-grained because much of the material incorporated in the flow was coarse-grained material entrained from the preexisting drainage channel bottom.

#### Sequence of Deposition

The brown debris-flow deposit is evident in the photograph shown in Figure 26, taken 2 days after the landslide event, as a thin, wide swath of dark-colored debris. The color of the deposit is due to its organic content and due to the wetness of the material at the time of the photograph. The gray debris-flow deposit is exposed as a narrower, light gray swath within and on top of the brown debris-flow deposit. The photograph suggested that the brown debris-flow deposit was laid down and subsequently covered by the gray debris-flow deposit.





Figure 26. Landslide deposits just below the source area of the Pyramid Guard Station landslide. The photograph (M. Kuehn) was taken 2 days after the landslide event of June 4, 1983. Dark-colored brown debris-flow deposit is located at the margins of landslide and light-colored gray debris-flow deposit at the interior. Note minor gully cut through interior of landslide and snow-bank beyond landslide margin.

The diagram in Figure 27 depicts the stratigraphic relationships exposed in the wall of a pit excavated at an elevation of approximately 7,310 feet just below the source area. The gray debris-flow deposit clearly overlies the brown debris-flow deposit, which is underlain by topsoil and colluvium.

The brown debris-flow deposit was derived from the eastern scarp in the source area and primarily involves topsoil material. The gray debris-flow deposit was derived from the western scarp in the source area and primarily involves colluvial and weathered bedrock material.



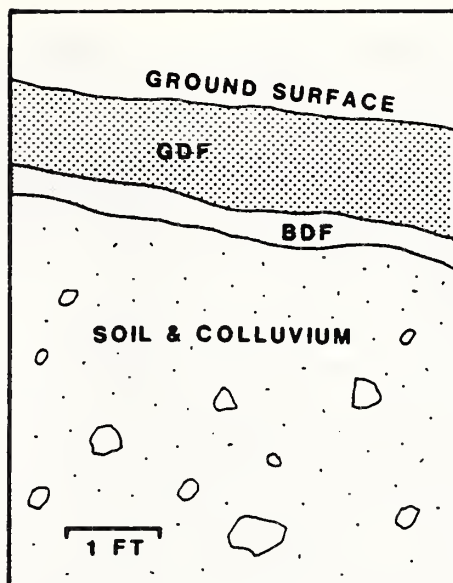


Figure 27. Cross-sectional sketch of wall of pit located below Pyramid Guard Station landslide source area. Gray debris-flow deposit overlies brown debris-flow deposit. The landslide deposits are underlain by topsoil and colluvium.

The western scarp clearly cuts across the slightly lower eastern scarp. The relationship of the scarps indicates that gray debris-flow failure occurred after the brown debris-flow failure.

#### Failure Analysis and Landslide Reconstruction

An oblique aerial photograph taken about 10 days after the Pyramid Guard Station landslide event is shown in Figure 28. The photograph indicates that the snowline was very close to the source area of the landslide at the time of its failure. This snow level evidence, supported by temperature and stream gauge data presented in Figure 8,





Figure 28. Aerial photograph of Pyramid Guard Station landslide taken approximately ten days after the landslide event (D. Totheroh). Note that the snowline is very near the source area of the landslide.

suggests that groundwater levels were abnormally high within the source area preceding the landslide failure.

The source area of the Pyramid Guard Station landslide is in a minor topographic swale where surface runoff and groundwater probably were concentrated. A subsurface stratigraphic sequence of highly permeable soil and colluvium underlain by less permeable weathered



bedrock occurs in the source area. A more deeply weathered soil profile occurs near the center of the swale, in the area of the initial failure.

The initial debris-flow failure of the Pyramid Guard Station landslide was likely triggered by rising groundwater levels. A perched water table probably developed on top of the interface between the relatively impermeable weathered bedrock and the permeable overlying soil and colluvium due to rapidly melting snow. At a critical groundwater level, the shallow layer of soil and colluvium began to slip, and mobilized as a rapid debris flow.

Debris that was mobilized from the center of the swale flowed through a stand of trees encircling the lower edge of the swale, scraping away bark along the base of many of the trees as it passed. The initial debris flow laid down the brown debris-flow deposit. The brown debris flow spread out significantly as it progressed down the smooth unchannelled slope below the swale (indicating that the flow apparently was relatively fluid). The initial flow caused relatively little erosion as it moved downslope, laying a thin veneer of debris on top of existing soil and vegetation.

The secondary failure may have occurred instantaneously after or within a very short time of the initial failure. Patrolman White, who witnessed the debris-flow front of the landslide as it passed over U.S. Highway 50, described a large initial flow and relatively minor surging afterwards. Apparently the initial and secondary flows combined down the channel to form one distinct debris-flow front by the time it crossed the highway.



The secondary failure involved primarily colluvial and weathered bedrock materials derived from the less-deeply weathered, western margin of the swale. The secondary debris flow laid down the gray debris-flow deposit as a relatively narrow deposit over the initial, brown debris-flow deposit. The secondary, gray debris flow did not spread out like the initial, brown debris-flow even though the flows involved similar volumes of material. It might be inferred, therefore, that the secondary debris flow was less fluid than the initial debris flow.

At an elevation of 6,880 feet, both of the flows were constricted into a narrow gully bounded by bedrock ridges to either side. Apparently the materials were thoroughly mixed as they entered the gully, so that only one debris-flow deposit can be distinguished below that point. The field evidence, therefore, supports the idea that only one main debris-flow front passed through the lower reaches of the drainage channel.

Below the gully, the debris flow entered a significant drainage channel, at an elevation of 6,730 feet, that originates in the bowl to the east of the source area. The debris flow generally remained confined to the drainage until it reached an elevation of approximately 6,400 feet. The debris flow spread out slightly above a bend in the channel at its junction with another channel from the east, at an elevation of approximately 6,300 feet.

The debris flow again remained confined to the drainage until it reached another bend in the channel at the top of an older abandoned channel at an elevation of 5,990 feet. The flow generally remained confined to the channel below 5,930 feet until it reached the South Fork



of the American River. A significant amount of debris, however, spilled onto U.S. Highway 50, closing it for a day.

The debris flow had sufficient force to destroy the series of rock check dams constructed above the highway and carry debris from the dams all the way to the South Fork of the American River. The debris flow, however, did not significantly damage the highway. The check dams have subsequently been rebuilt by the U.S. Forest Service in the locations shown on Plate 2. The highway culvert for the Pyramid Guard Station drainage channel has been replaced with a larger capacity culvert to serve anticipated greater flood conditions.



## MECHANICS

The Strawberry Creek and Pyramid Guard Station landslides involved predominantly sand and coarse debris which flowed in the manner of a viscous fluid at rapid speeds. The landslides, therefore, may be classified as debris flows according to the landslide classification system of Varnes (1978). Evidence that the Strawberry Creek landslide attained sufficient speeds for it to become airborne, such as that shown in Figure 13, indicates that it may more accurately be classified as a debris avalanche.

The initial debris-flow failures for both landslides occurred within topsoil and colluvial materials apparently as rising groundwater levels reached critical levels. Secondary failures for both landslides occurred within bedrock materials probably as a result of a combination of high groundwater levels and undermining caused by the initial failures. A mechanical analysis is performed for the initial landslide failures only.

The initial landslide failures are similar to "soil slip/debris flows" described by Campbell (1975) in which "a slab of soil becomes detached at an underlying slip surface and at the margins and begins moving, part or all of the mass is effectively remolded by its own motion, and it changes from a rigid slab to a viscous fluid", or debris flow.



The initial rupture surfaces of the Strawberry Creek and Pyramid Guard Station landslides are planar surfaces approximately parallel to the preexisting ground surfaces. Field evidence within the source area scars indicates that the landslide rupture surfaces occurred on or near the interface between weathered bedrock material and overlying soil and colluvium. The depths of the initial failures are small relative to the length of the rupture surfaces. Therefore, an infinite slope analysis of the failures is appropriate.

Highly permeable soil and colluvial materials in the source areas of the Strawberry Creek and Pyramid Guard Station landslides are underlain by much less permeable weathered granodiorite bedrock. According to Campbell (1975), a perched groundwater table may develop when the groundwater infiltration rate of the soil mantle is greater than the infiltration rate of the underlying parent material. These conditions apparently occur in the source areas of the Strawberry Creek and Pyramid Guard Station landslides. An assumption of steady groundwater flow parallel to the interface between the bedrock and overlying soil and colluvium is made in the analyses of the failure mechanics for the two landslides.

The soil and colluvial materials in the source areas are very loose and granular and contain little to no clay. At most, 1% clay was measured by hydrometer tests on the finer-grained size fractions of 4 samples of debris-flow deposits. The sieve tests performed on the coarser-grained size fractions of 31 samples of debris-flow deposits indicate that less than 10% silt- and clay-sized material was involved in the debris flows. The sieve analyses also suggest that very small



percentages of clay were involved in the debris flows. The minor amount of clay involved in the Strawberry Creek and Pyramid Guard Station landslides is in agreement with other studies by Sharp and Nobles (1953), and Lawson (1982) who found less than 3% clay-sized material in debris-flow deposits.

The diagram presented in Figure 30 (after Campbell, 1975) depicts an idealized subsurface profile of weathered bedrock and overlying colluvial and soil material, such as that encountered in the source areas of the subject landslides. The contact between the weathered bedrock and the overlying colluvial and soil material is depicted as a potential sliding surface in the diagram.

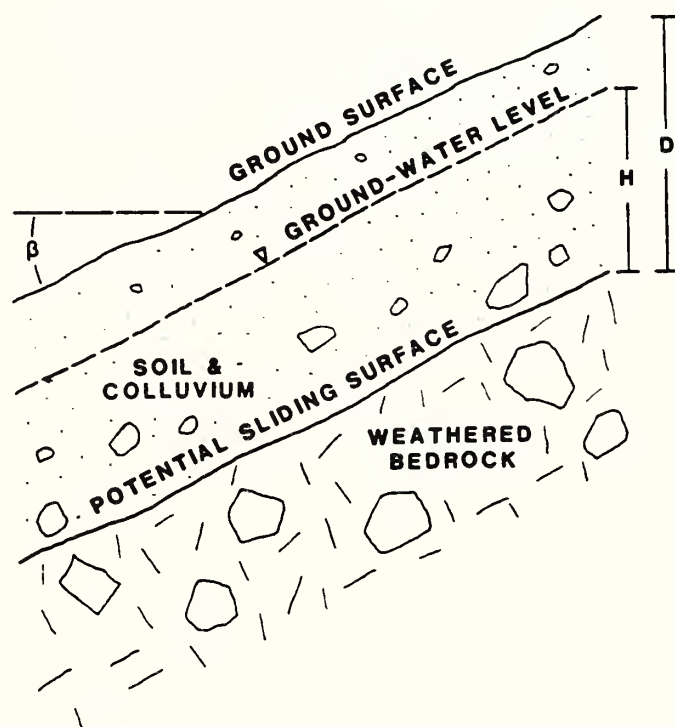


Figure 30) Diagram showing idealized cross-section of subsurface materials prior to soil slip (after Campbell, 1975).



In an infinite slope analysis (Morgenstern and Sangrey, 1978), sliding occurs along a planar surface and end effects are neglected. It is assumed that the failed material moves in a translational manner in which there is little internal deformation. There is considerable internal deformation in a debris flow, as material that has failed turns into a viscous fluid. However, the infinite slope analysis is considered valid for the initial stages of movement, or soil slip, prior to mobilization as a debris flow.

The in-situ soil and colluvial material of depth (D) is located on a slope of ( $\beta$ ), with a groundwater level above the potential sliding surface of (H) prior to the landslide failure. The soil and colluvial materials involved in the subject landslides lacked clay, therefore, cohesion will be considered negligible in the analyses.

The stability of a body of soil, where steady groundwater flow is occurring parallel to the slope at shallow depths, may be represented by a form of Terzaghi's (1950) equation for resistance to shear, developed by Skempton and DeLory (1957):

$$FS = \left( 1 - \frac{H \sigma_w}{D \sigma_s} \right) \frac{\tan \phi}{\tan \beta} \quad \text{Equation 1}$$

Where: FS = factor of safety  
 H = height of ground-water table above sliding surface  
 D = depth of sliding surface  
 $\sigma_w$  = unit weight of water  
 $\sigma_s$  = unit weight of soil  
 $\phi^s$  = angle of internal friction of soil  
 $\beta$  = slope angle



Failure of the body of soil occurs when the factor of safety is less than 1. Therefore, Equation 1 is rewritten at the time of failure, where FS = 1, as:

$$H = D \left( \frac{1 - \tan \beta}{\tan \phi} \right) \frac{\sigma_s}{\sigma_w} \quad \text{Equation 2}$$

Using Equation 2 and known or estimated quantities, the height (H) of the water table above the rupture surfaces for both the Strawberry Creek and Pyramid Guard Station landslides at the time of their failures may be solved.

Samples of in-situ soil and colluvium (samples 19 through 23) were gathered in the source area of the Strawberry Creek landslide from the locations shown on Plate 1. A standard steel sampling tube was driven with a hand hammer device to collect relatively undisturbed samples in 4 inch long, 1.5 inch diameter, brass liners. The liners were sealed and brought back to the lab for testing. The results of moisture content and dry density determinations are presented in Table 2.

TABLE 2 - MOISTURE CONTENT AND DENSITY DETERMINATIONS

<u>Sample #</u>	<u>Depth</u>	<u>Moisture Content</u>	<u>Wet Density</u>	<u>Dry Density</u>
19	2"	7%	83 pcf	80 pcf
20	1"	9%	70 pcf	64 pcf
21	1"	7%	76 pcf	71 pcf
22	1"	16%	63 pcf	54 pcf
23	<u>24"</u>	<u>7%</u>	<u>104 pcf</u>	<u>96 pcf</u>
average:	6"	9%	79 pcf	72 pcf



The average dry density of 72 pcf was determined for the five samples of soil. Because only very loose surficial soils were sampled, the dry density probably is low and does not accurately represent the average dry density of the soil and colluvial material involved in the landslide failures. Lumb (1962) indicated that granitic soils typically have an average dry density of approximately 120 pcf.

Based upon the dry density determinations listed above and upon Lumb's estimate, an average unit weight or dry density of 100 pcf was used in the failure analyses of the initial failure. The soil materials in the source areas of both landslides are similar, therefore, a unit weight of 100 pcf will also be used in the analyses of the initial failure of the Pyramid Guard Station landslide.

According to Lumb (1962), cohesionless granitic soils typically have an angle of internal friction of 37 degrees. Lambe and Whitman (1969, p. 149) also indicated that the friction angle for well-graded sand commonly varies between 30 and 34 degrees. The in-situ soil materials derived from weathered granodiorite in both of the initial landslide failures are relatively loose, well-graded sands. A friction angle ( $\phi$ ) of 37 degrees was used in the failure analyses. This value may be low since root strength may have contributed to the strength of the soil material.

Equation 2, describing the height of the groundwater level above the potential sliding surface, was solved using the quantities for the respective landslides listed in Table 3.



TABLE 3 - VARIABLES FOR FAILURE ANALYSES

	<u>Strawberry Creek</u>	<u>Pyramid Guard Station</u>
D (feet)	5	4
$\beta$ (degrees)	31	26
$\Phi$ (degrees)	37	37
$\sigma_s$ (pcf)	100	100
$\sigma_w$ (pcf)	62	62

Solving Equation 2 for the Strawberry Creek and Pyramid Guard Station landslides, groundwater levels (H) of 1.6 feet and 2.3 feet, respectively, are calculated. Given that slope was the only significant variable in the analyses between the two respective landslides, it is clear that slope controls the groundwater level required to induce failure. The source area of the Pyramid Guard Station landslide is more gentle than the Strawberry Creek landslide source area (26 degrees versus 31 degrees), therefore, a higher groundwater level is required for the failure of the Pyramid Guard Station landslide.



## DISCUSSION

### Landslide Initiation

The data presented here indicate that the Strawberry Creek landslide and the Pyramid Guard Station landslide were initiated or triggered by unique snowmelt conditions. A record snowpack that accumulated in the Sierra Nevada during the 1982-1983 winter persisted on the upper mountain slopes into the Spring of 1983. The two-week-long heatwave during late May and early June of that year produced snowmelt conditions in which record stream levels were measured in the South Fork of the American River, downstream from the study areas. No significant rainfall was recorded during the time period immediately preceding the landslide failures. In addition, no seismic activity was associated with the failures. Therefore, it is inferred that the Strawberry Creek and Pyramid Guard Station landslides were triggered by unusual snowmelt conditions that generated high ground-water conditions within the source areas of the landslides.

Sharp and Nobles (1963) described an example of snowmelt-generated debris flows at Wrightwood, California. The Wrightwood debris flows involved progressive surging of debris over several days. The Strawberry Creek and Pyramid Guard Station landslides, in contrast, involved two or three discreet landslide events over a short time period.



Harr (1981) and Swanston (1974) indicated that landsliding may be associated with snowmelt induced by rainfall. However, the subject landslides occurred as a result of snowmelt induced exclusively by radiant solar energy.

### Landslide Characteristics

The Strawberry Creek and Pyramid Guard Station landslides have several characteristics which have intriguing similarities and significant contrasts. Several of these characteristics are listed in Table 4.

#### Similarities

The Strawberry Creek and Pyramid Guard Station landslides failed on similar dates, within 5 days of one another. Both landslides occurred in the same general location, within 4 miles of one another, and are located on similar southwest-facing mountain slopes. The source areas of the landslides are situated at almost identical elevations, with their crowns within 10 feet of one another.

Because the source areas for the landslides are located at similar elevations on similar southwest-facing slopes, the respective source areas probably received similar amounts of snowpack. In addition, the source areas probably experienced similar temperature and snowmelt conditions in the spring. The southwest-facing slope aspect allows for



TABLE 4 - LANDSLIDE CHARACTERISTICS

SIMILARITIES

Date of Landslide Failure  
 Location  
 Southwest-Facing Slope  
 Source Area Elevation  
 Snowpack  
 Temperature  
 Snowmelt Condition  
 Granodiorite Parent Material  
 Debris-Flow Mechanism  
 Successive Failures  
 Two Distinct Deposits

CONTRASTSStrawberry CreekPyramid Guard Station

31 Degree Slope At Source	-	26 Degree Slope At Source
Break-In-Slope At Source Area	-	Swale At Source Area
Forested Source Area	-	Brushland Source Area
Not Recently Burned	-	Recent Burn History
No Previous Recent Landsliding	-	Recurrent Landsliding
Relatively Unchanneled Flow	-	Strongly Channeled Flow

a maximum exposure to radiant solar energy to melt the snowpack. The landslides failed near the end of the two-week-long heatwave after groundwater levels probably rose significantly due to melting snow.

The respective landslides initiated within materials weathered from similar granodiorite parent materials and failed by similar debris-flow mechanisms. The landslides also involved successive failures which laid down two distinct debris-flow deposits: an initial, brown debris-flow deposit derived from failed soil material, and a secondary,



gray debris-flow deposit derived from failed colluvial and bedrock material.

## Contrasts

A break-in-slope is located within the source area of the Strawberry Creek landslide. Relatively even, planar surfaces occur above and below the break-in-slope. The initial failure occurred on a surface with a slope of approximately 31 degrees. The source area is forested and has no recent fire history. The debris flow was relatively unchannellized or unconfined to any preexisting drainage channel as it progressed downslope. No evidence of previous recent landsliding was found in the vicinity of the Strawberry Creek landslide.

In contrast, the source area of the Pyramid Guard Station landslide occurs within a swale on a slope of approximately 26 degrees. The source area is brush-covered and had recently been burned. The debris flow was strongly channellized or confined within a preexisting drainage as it progressed downslope. Similar debris flows have recurred within the vicinity of the Pyramid Guard Station landslide.

A simplified analysis of the two debris-flow failures showed that a higher groundwater level was required for the failure of the Pyramid Guard Station landslide than for the Strawberry Creek landslide. This was due to the more gentle slope of the source area of the Pyramid Guard Station landslide, in comparison to the steeper slope of the



source area of the Strawberry Creek landslide. It might be inferred, given similar drainage and snowmelt conditions, that the Pyramid Guard Station would fail after the Strawberry Creek landslide because it would take longer for groundwater levels to rise to the higher required level. In fact, the Pyramid Guard Station landslide failed five days after the Strawberry Creek landslide.

Contrasting topographies occur within the source areas of the respective landslides. A swale occurs within the source area of the Pyramid Guard Station landslide, whereas a previously described break-in-slope occurs within the source area of the Strawberry Creek landslide. These contrasting topographies, however, are areas where groundwater tends to accumulate within the respective source areas. The swale within the source area of the Pyramid Guard Station landslide tends to concentrate both surface water and groundwater. Several active springs located below the break-in-slope in the source area of the Strawberry Creek landslide also indicate that groundwater is concentrated in that area.

Fire may have been a significant contributing factor in the initiation of the Pyramid Guard Station landslide. Several researchers (Cleveland, 1973; DeBano et al., 1980; Durgin, 1985) have discussed the effects of fire in developing conditions conducive to debris-flow failures. Wildfires destroy vegetation that acts as a stabilizing ground cover and which removes excess groundwater from the soil. The heat from fire may also develop a nonwetable zone or groundwater barrier at depth within the soil so that water levels build up within the soil layer. It is interesting that charcoal fragments were



observed within several of the older debris-flow deposits which were examined in the trench and stream-bank exposure of the Pyramid Guard Station landslide. Apparently wildfires may also have been a contributing factor to ancient debris flows within the Pyramid Guard Station drainage.

observed within several of the other debris-flow deposits which were  
examined in the trench and stream-bed exposure of the front of the  
Station landslide. Apparently, within any one debris flow, a  
contributing factor to material debris flow within the front of the  
Station drainage.

## CONCLUSION

The Strawberry Creek and Pyramid Guard Station landslides are catastrophic debris-flow landslides which occurred in the Sierra Nevada during the spring of 1983 following a record snowfall season. Climatic conditions were the dominant factors controlling the initiation of both landslides. High groundwater levels developed in the landslide source areas as a result of rapidly melting snow during a two-week-long heatwave. The high groundwater levels triggered shallow soil slips which were mobilized as debris flows.

The soil slips occurred within topsoil and colluvial materials derived from weathered granodiorite bedrock. The debris flows travelled over 1/2 mile down mountain slopes, causing extensive damage along their paths, before being deposited into stream drainages below. Secondary debris-flow failures that incorporated weathered bedrock materials followed the initial failures of each landslide. Distinctive debris-flow deposits were associated with the initial and secondary debris flows of each landslide. Grain size analyses indicate that the debris flows involved noncohesive silty gravelly sands with less than 1% clay-sized material.

Evidence from recent and older debris-flow deposits in the Pyramid Guard Station drainage indicate that debris-flow landsliding has been a recurrent phenomena in the drainage. Five recent debris-flow events have been recorded in the last 325 y.b.p. Two older debris-flow events have been dated at 1770 and 2085 y.b.p.



Significant findings developed in this study include:

1. Snowmelt generates debris-flow landslides in the Sierra Nevada.
2. Debris flows may occur in weathered granitic materials containing less than 1% clay.
3. Debris-flow landsliding has been a recently recurrent phenomena in the Sierra Nevada.



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# APPENDIX A: LIST OF AERIAL PHOTOGRAPHS

<u>Flight Number</u>	<u>Photograph Pair</u>	<u>Date</u>	<u>Scale</u>	<u>Color</u>	<u>Coverage</u>
?	EPF-10-26 & 27	9/05/65	1:15,840	B/W	PGS
?	EPF-14-54 & 55	8/13/66	1:15,840	B/W	PGS
?	EPF-14-195 & 196	8/13/66	1:15,840	B/W	SC
HAP2 06017	0773 112 & 113	7/25/73	1:62,000	B/W	SC & PGS
USDA 24 615030	380-102 & 103	8/28/80	1:18,500	COLOR	SC
USDA 24 615030	380-161 & 162	8/28/80	1:18,500	COLOR	PGS
USDA 12 615036	1182-103 & 104	9/04/83	1:12,000	COLOR	PGS
USDA 12 615036	1182-140 & 141	9/04/83	1:12,000	COLOR	SC

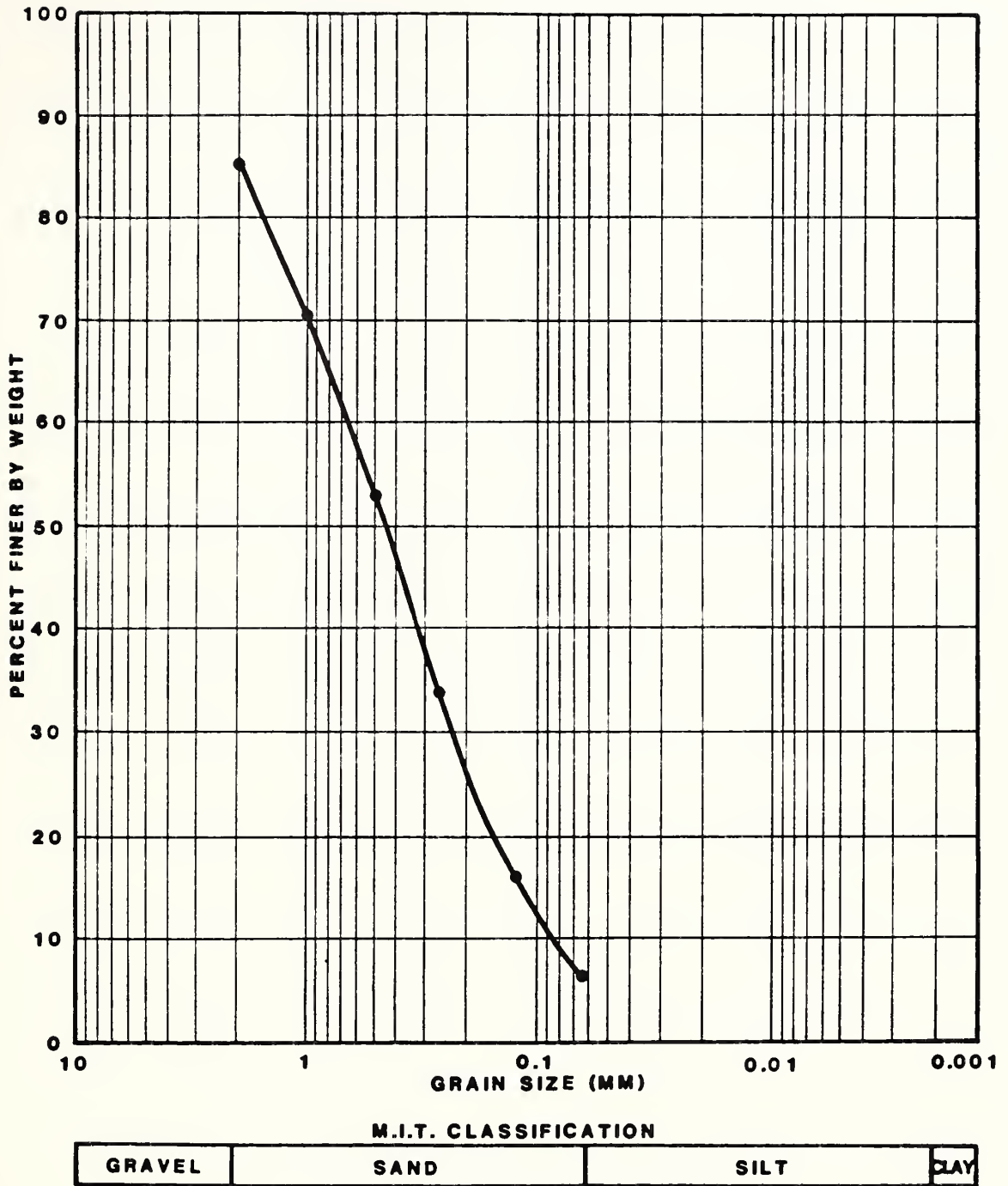
Note: PGS = Pyramid Guard Station landslide

SC = Strawberry Creek landslide



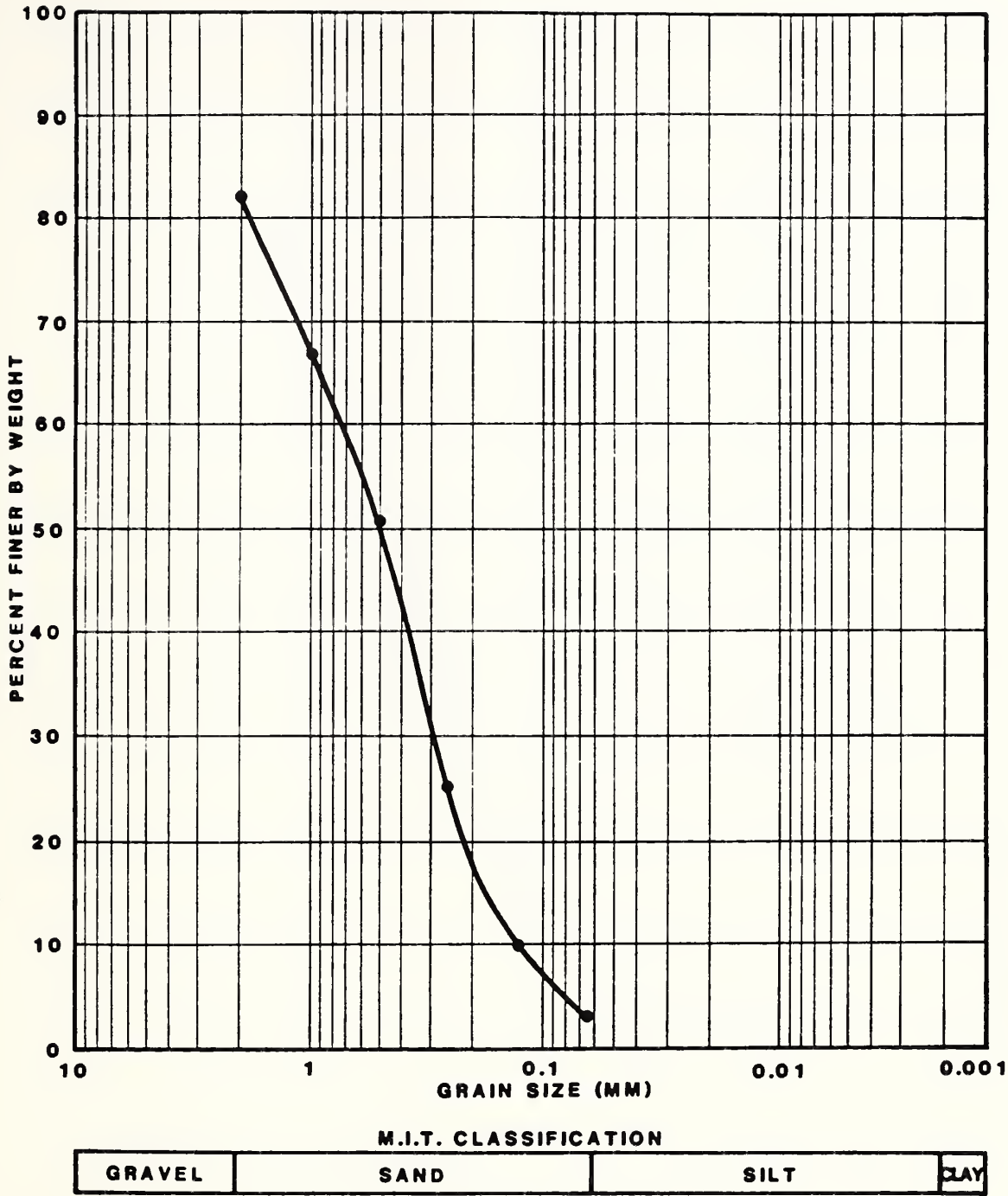
## APPENDIX B: GRAIN SIZE DISTRIBUTION CURVES





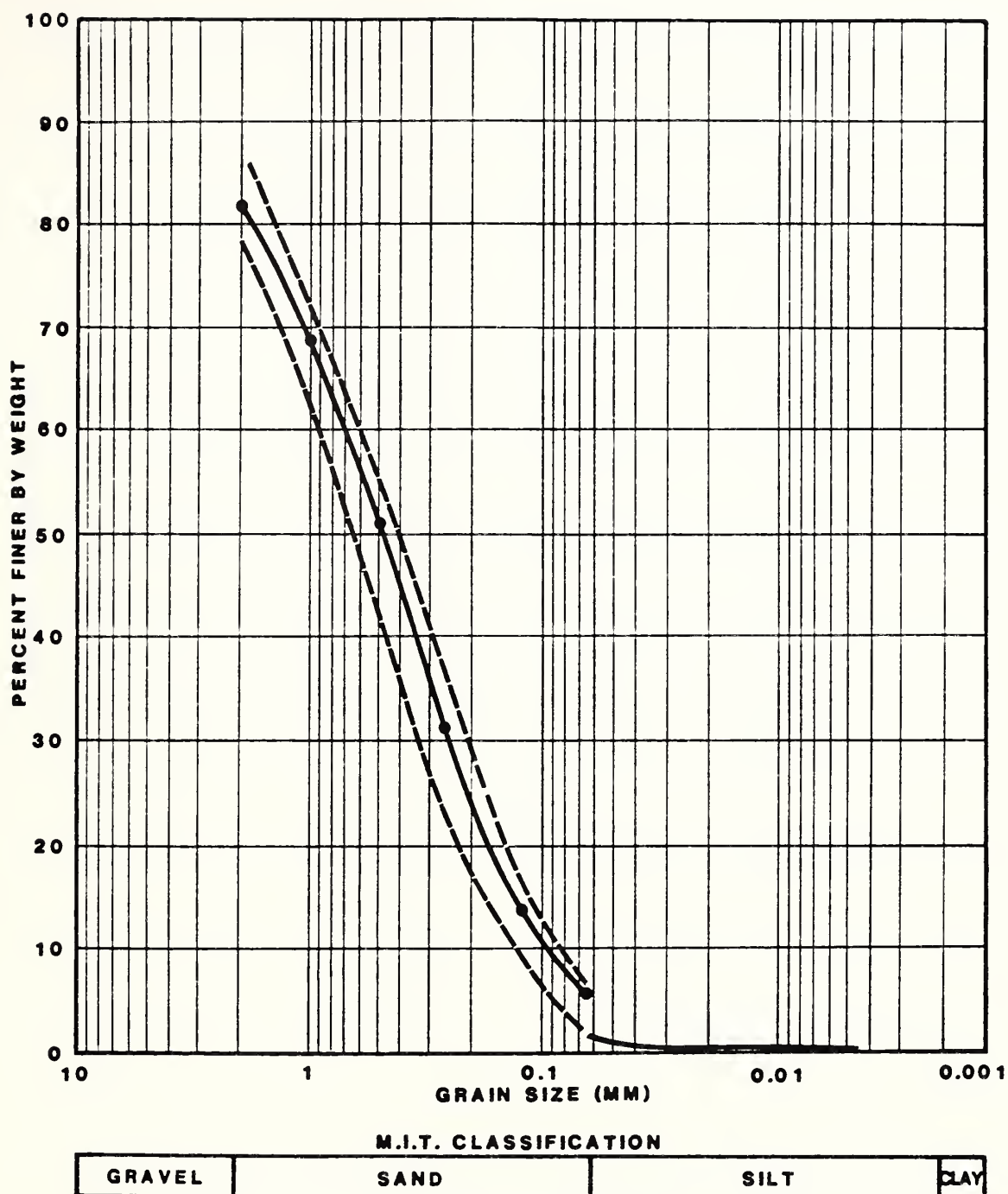
Graph 1. Strawberry Creek landslide sample 1: Ledford-Notned outcrop complex soil (points indicate sieve size openings).





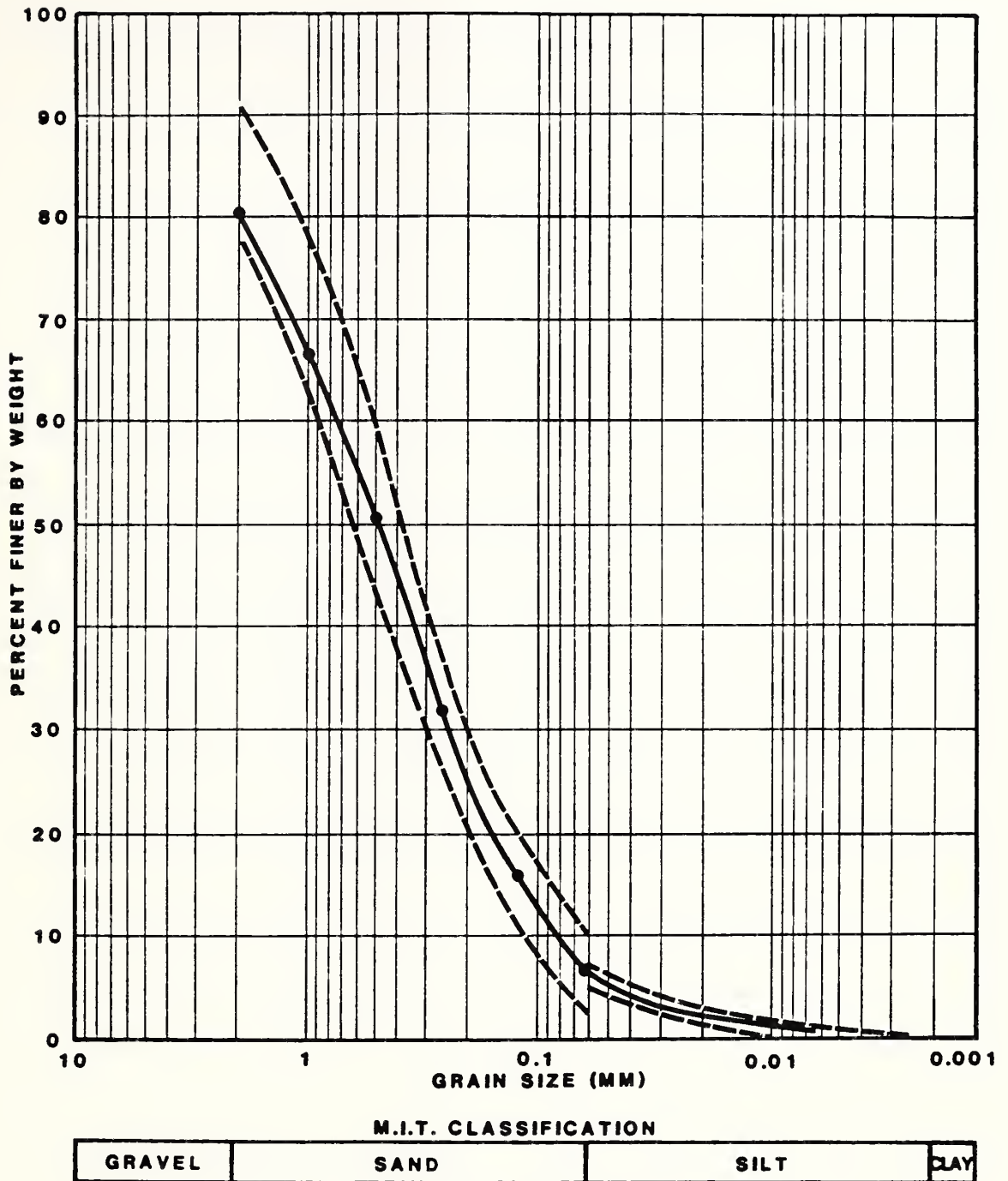
Graph 2. Strawberry Creek landslide sample 9: Lithic Xerumbrepts-Rock outcrop complex soil (points indicate sieve size openings).





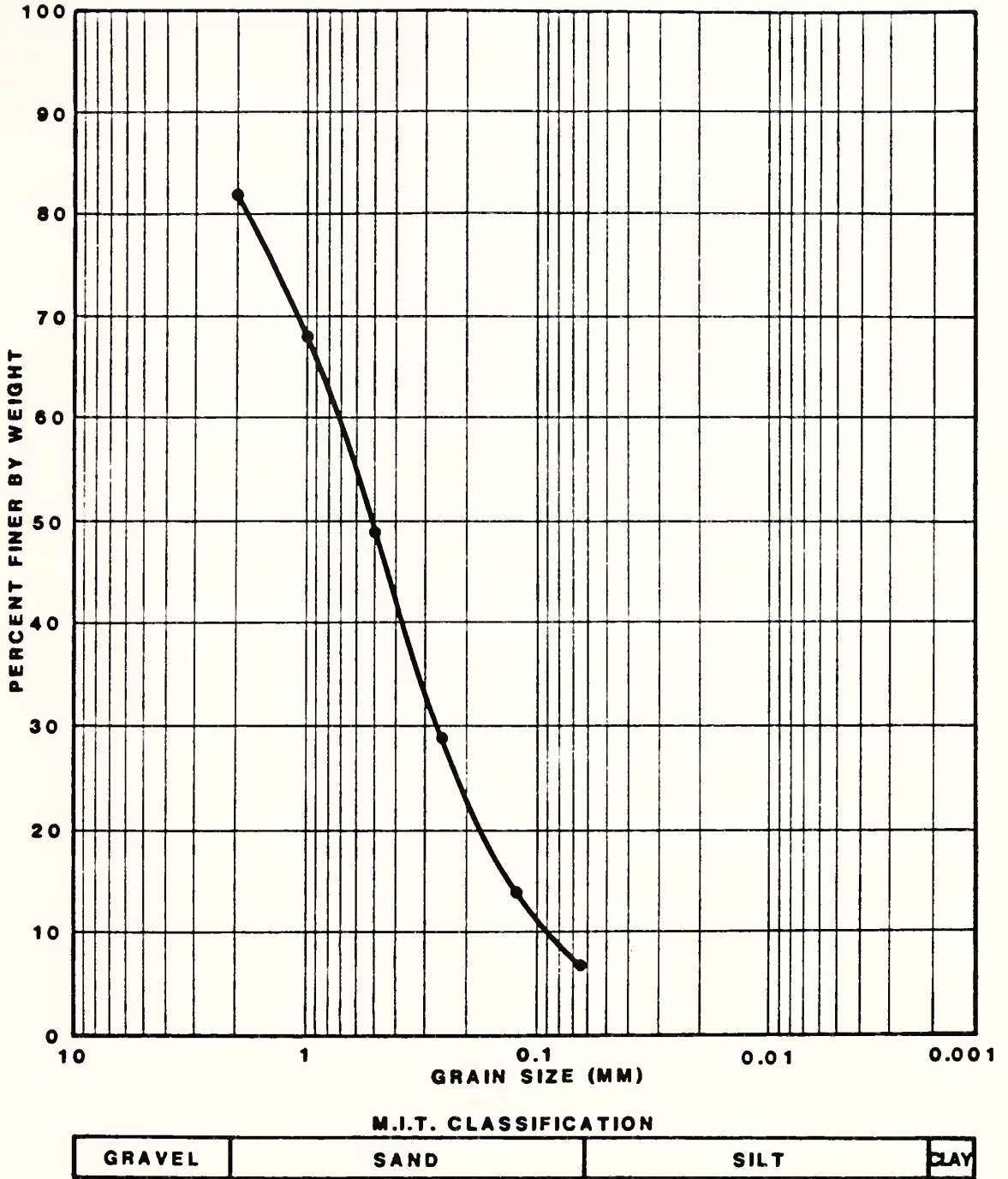
Graph 3. Strawberry Creek landslide: brown debris-flow deposit (points indicate sieve size openings, solid line indicates average curve, dashed lines indicate range, hydrometer analysis shown as solid line).





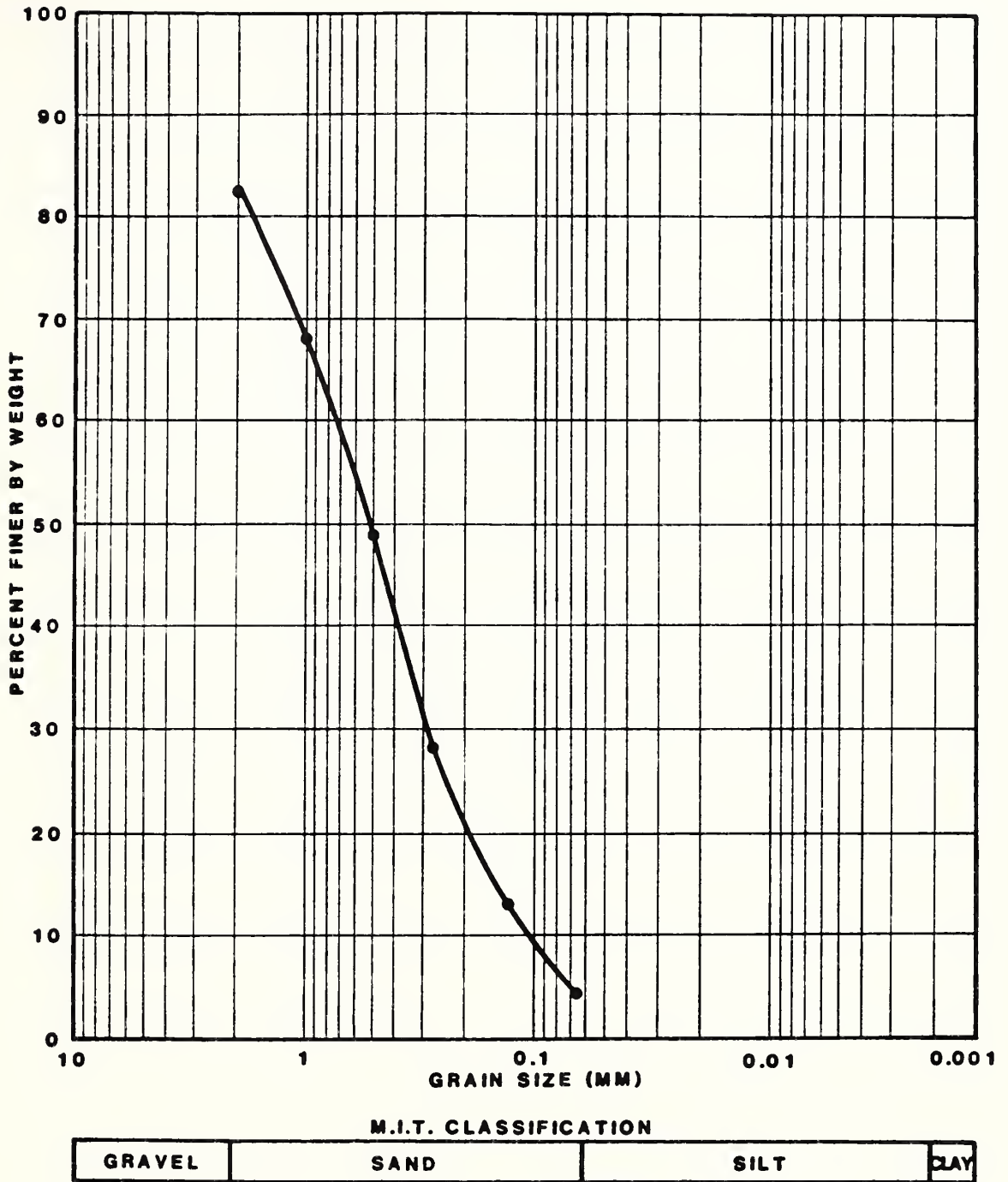
Graph 4. Strawberry Creek landslide: gray debris-flow deposit (points indicate sieve size openings, solid line indicates average curve, dashed lines indicate range, average hydrometer analysis shown as solid line with range as dashed lines).





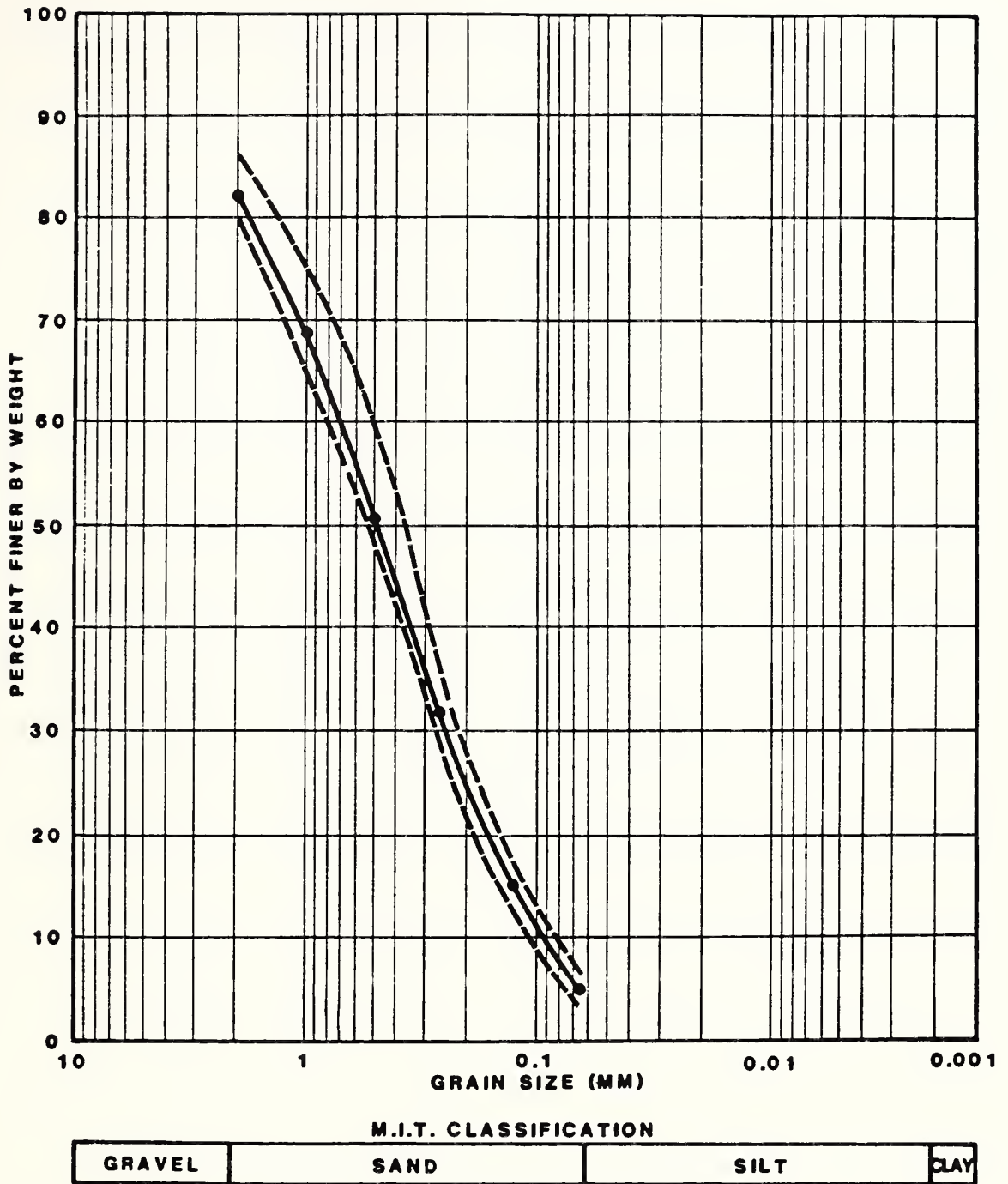
Graph 5. Pyramid Guard Station landslide sample 1: Lithic Xerumbrepts-Rock outcrop complex soil (points indicate sieve size openings).





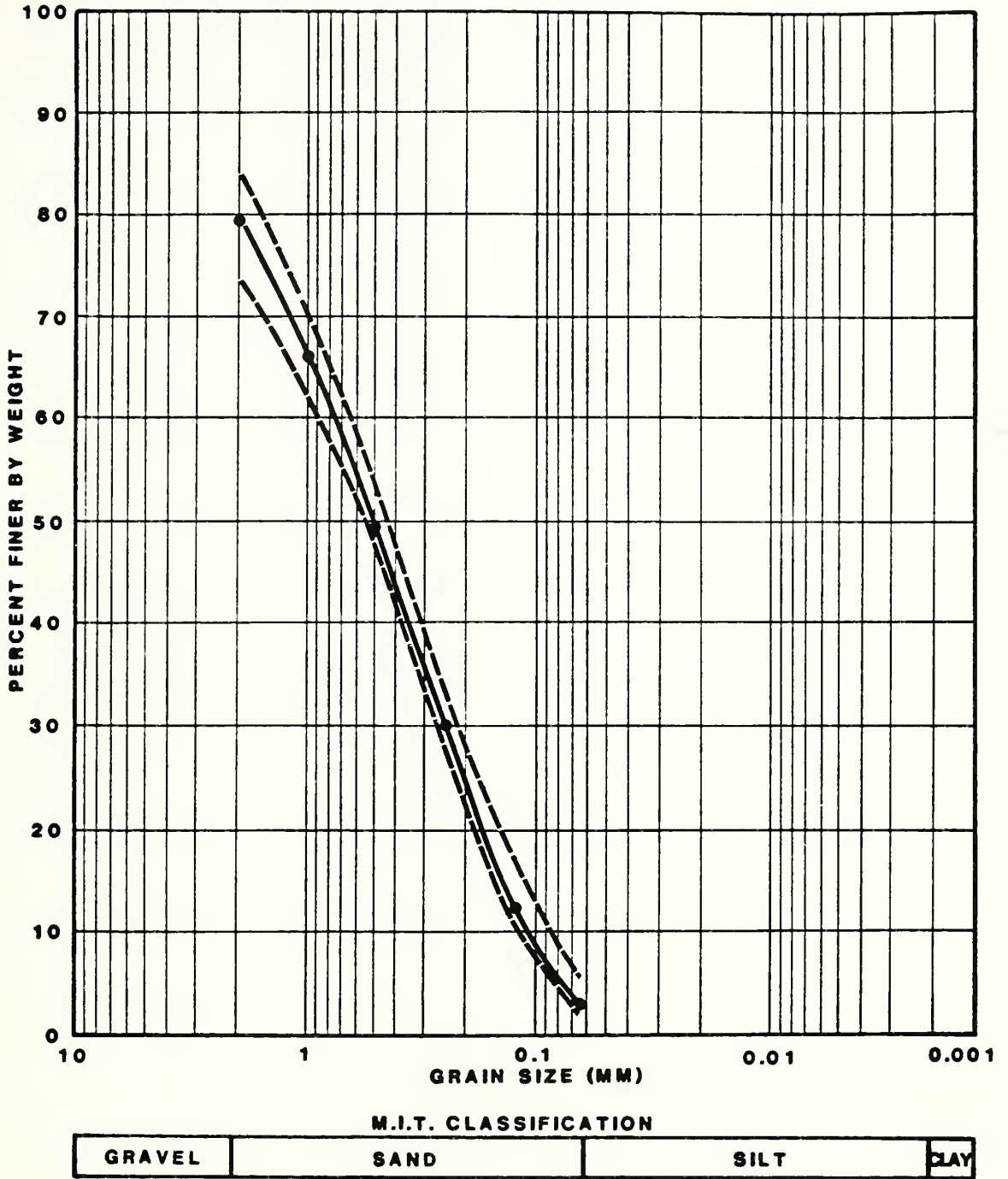
Graph 6. Pyramid Guard Station landslide sample 7: Lithic Xerumbrepts-Rock outcrop complex soil (points indicate sieve size openings).





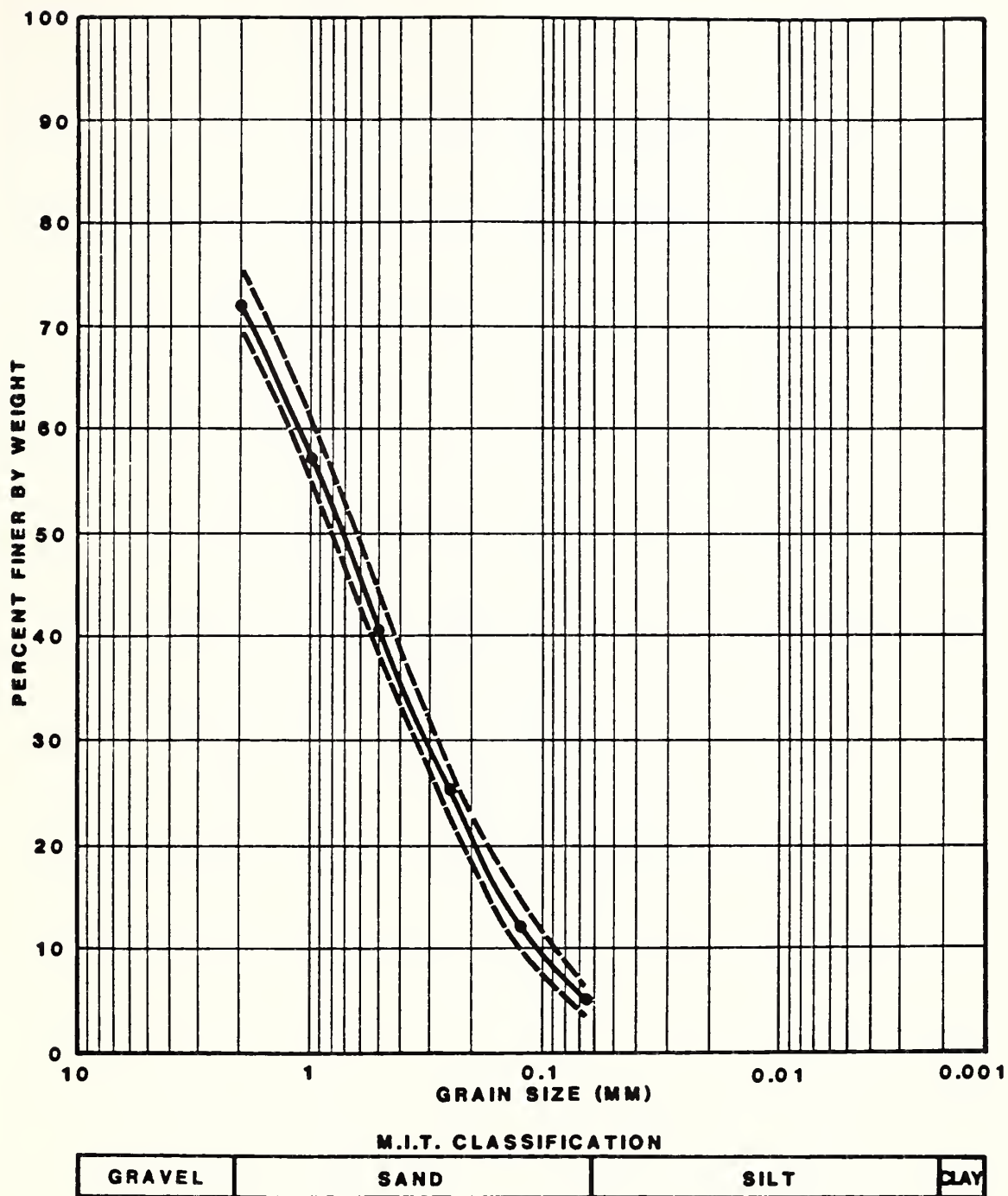
Graph 7. Pyramid Guard Station landslide: brown debris-flow deposit (points indicate sieve size openings, solid line indicates average curve, dashed lines indicate range).





Graph 8. Pyramid Guard Station landslide: gray debris-flow deposit (points indicate sieve size openings, solid line indicates average curve, dashed lines indicate range).





Graph 9. Pyramid Guard Station landslide: undifferentiated debris-flow deposit (points indicate sieve size openings, solid line indicates average curve, dashed lines indicate range).



# EXPLANATION

## SURFICIAL GEOLOGY

- 815 DRANDODITE BEDROCK
- 820 SOIL COLLUVIUM
- 821 ALLUVIUM

## LANDSLIDE DEPOSITS

- 821 BROWN DEBRIS FLOW
- 821 GREY DEBRIS FLOW

## EROSIONAL SURFACES

- 18 SUPRINE SURFACE
- 8 DUFFY
- 82 SCURED GROUND

## MAP SYMBOLS

- GEOLOGIC CONTACT (IMAGED IN THE FIELD)
- GEOLOGIC CONTACT (IMAGED FROM AIR PHOTOGRAPH)
- BED OF FUTURE SURFACE
- TENSION CRACK
- SPRING
- EXPLORATION PIT
- SOIL BERM(S)
- MOUND
- SLOPE INDICATOR

— OBSERVED FEE (IN DIRECTION OF STREAM)



Scale 0 200 400 Feet



## STRAWBERRY CREEK LANDSLIDE El Dorado National Forest, California By Steven F. Connolly, June 1988

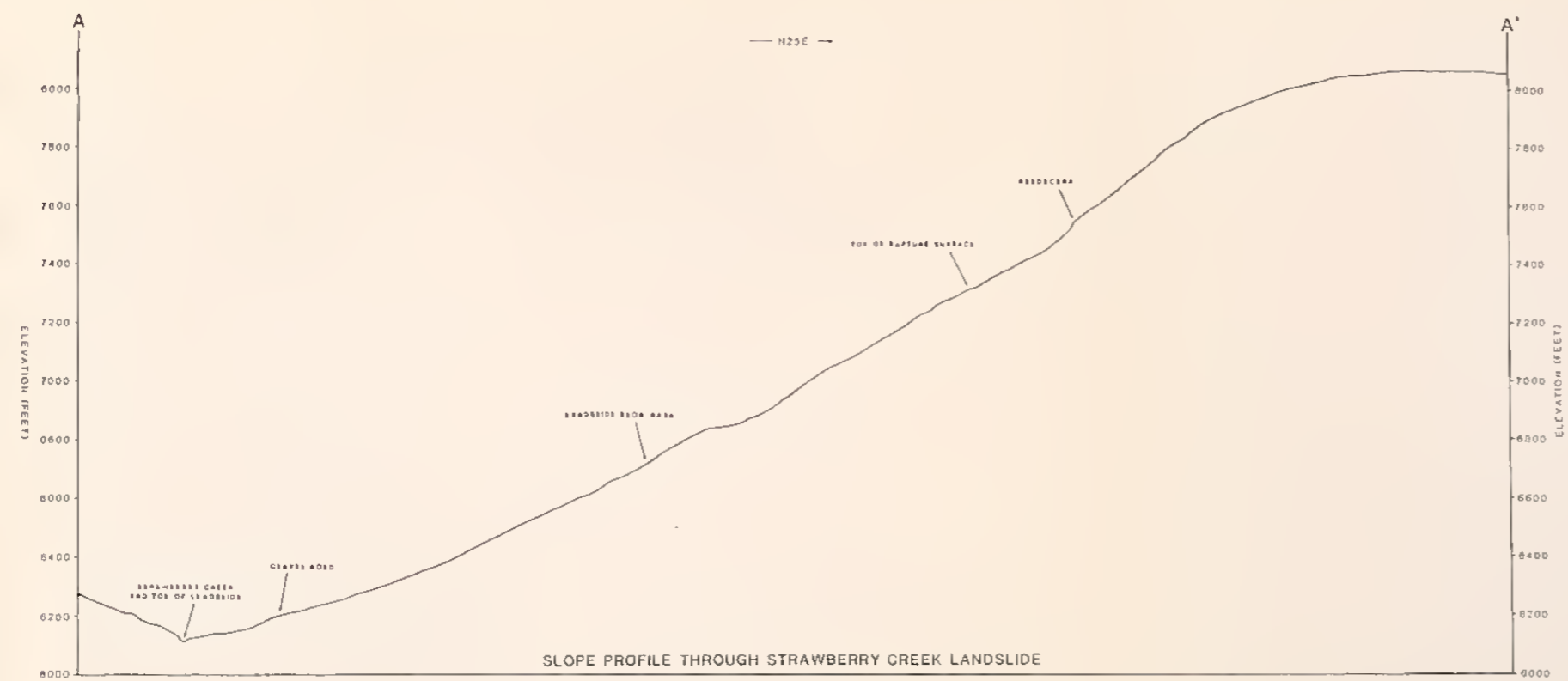
Base Map - U.S. Forest Service Geomtronics  
Contour Interval - 20 Feet  
Supplemental Contours - 10 Feet  
Compilation Scale - 1:3000  
Map Scale - 1:2400, 1 Inch = 200 Feet  
Geology Mapped 1985



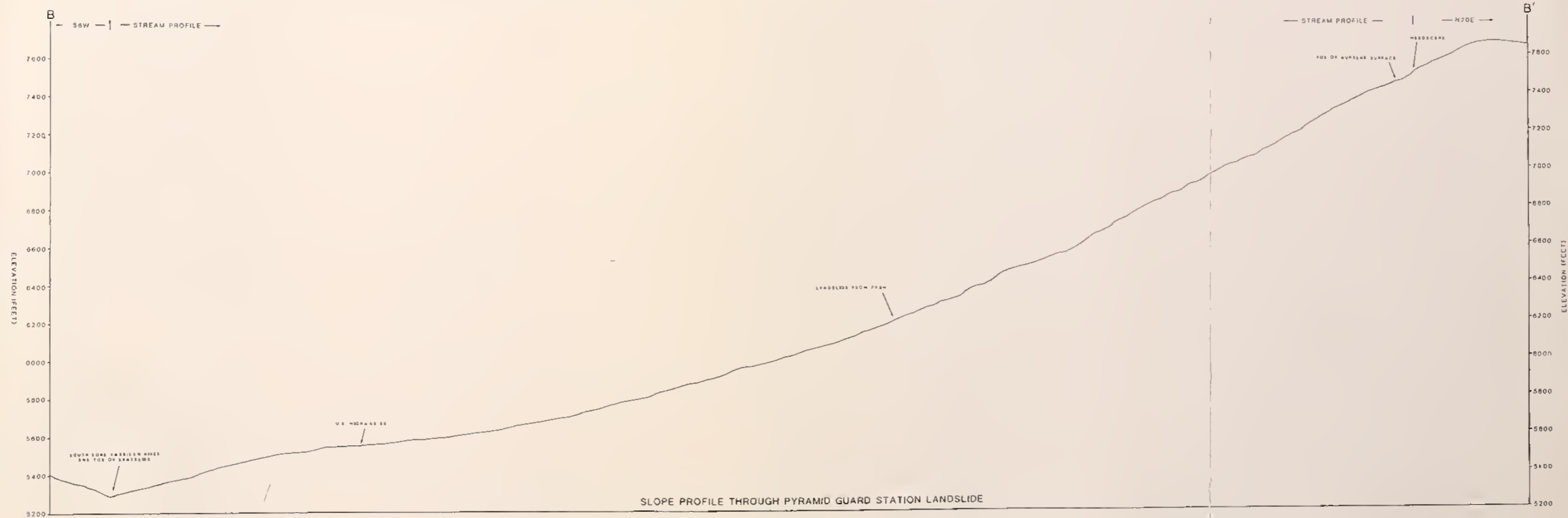








**SLOPE PROFILES A-A' AND B-B'**  
 STRAWBERRY CREEK AND PYRAMID GUARD STATION LANDSLIDES  
 By Steven F. Connelly, June 1988  
 Base - U.S. Forest Service Geomatics  
 Scale - 1 Inch = 200 Feet





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Maile Neel





